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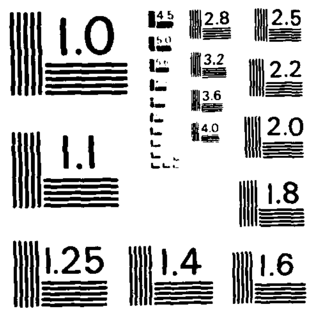

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AFWAL-TR-82-3040,
Part III

DEVELOPMENT AND FLIGHT TEST OF AN ACTIVE FLUTTER SUPPRESSION SYSTEM FOR THE F-4F WITH STORES

PART III, FLIGHT DEMONSTRATION OF THE ACTIVE FLUTTER SUPPRESSION SYSTEM

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June 1983

Final Report for Period March 1980 - December 1980

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFWAL-TR-82-3040, Part III	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Active Flutter Suppression System for the F-4F with Stores, Part III. Flight Demonstration of the Active Flutter Suppression System		5. TYPE OF REPORT & PERIOD COVERED Final Report March 1980-December 1980 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) H. Hönlinger, D. Mussman, R. Manser and L. J. Huttsell		8. CONTRACT OR GRANT NUMBER(s) Memorandum of Understanding
9. PERFORMING ORGANIZATION NAME AND ADDRESS Messerschmitt-Bolkow-Blohm GmbH. (MBB) Ottobrunn, Federal Republic of Germany		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS PE 62201F 2401/02/23
11. CONTROLLING OFFICE NAME AND ADDRESS Flight Dynamics Laboratory (AFWAL/FIB) Air Force Wright Aeronautical Laboratories, AFSC Wright-Patterson Air Force Base, Ohio 45433		12. REPORT DATE June 1983 13. NUMBER OF PAGES 66
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Active Controls
Aeroservoelasticity
Flutter
Flutter Suppression
Wing/Store Flutter

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Extensive research programs have been conducted at MBB and at AFWAL to investigate the application of active controls for the suppression of wing/store flutter. A flutter suppression system was developed and flight tested on an F-4F aircraft. The control law was designed by MBB using optimal control theory to minimize the control surface motion and to provide the required stability margins. During the test it was found that the dynamic behavior of the wing-pylon-store changed considerably with excitation amplitude due to free

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play and preload. The active flutter suppression system worked well and provided an increase in flutter speed.

FOREWORD

The research described in this report was conducted by Messerschmitt-Bolkow-Blohm GmbH. (MBB) under a joint U.S. Air Force/German Ministry of Defense Memorandum of Understanding. The Air Force Project Engineers for this effort (Work Unit 24010223) were Thomas E. Noll and Lawrence J. Huttsell of the Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories. The MBB Project Engineer was H. Hönlinger.

The authors wish to acknowledge the cooperation and support of the OTC E-61 of the Federal Armed Forces in Manching and DFVLR, Institute for Aeroelastics, in Gottingen.

This report (Part III) documents the flight demonstration of the active flutter suppression system. Part I documents the design of the active flutter suppression system. Part II documents the ground vibration tests, the ground tests on the flutter suppression system, and the initial subcritical flight tests.

This report covers work conducted from March 1980 to December 1980.

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SECTION I

INTRODUCTION

During the last several years, considerable interest has emerged in the U.S. and European community for the application of active control technology to suppress flutter. Both the U.S. Air Force and MBB have performed extensive research programs accompanied by wind tunnel tests in the field of active flutter and elastic mode suppression.

In 1975, MBB conducted a successful wind tunnel test which also led to a flight demonstration. The research demonstrated suppression of wing/store flutter with store mounted vanes (Reference 1). During another program the flutter speed was increased on a fin-tailplane-aft fuselage with a hydraulically driven rudder (References 2, 3). Miniature model actuators and new wind tunnel test techniques were developed to investigate Flutter Suppression Systems (FSS) with flutter models. Special computer programs utilizing optimal control theory (Reference 4) were adapted to find suitable control laws for flutter suppression. A very successful application of these programs is described in Reference 5. Analytical development of systems to reduce buffet-induced pilot vibrations was presented in Reference 6. A system to improve ride comfort of a low wing loaded fighter was laid out recently (Reference 7).

Two full scale airplanes were equipped and flight tested to prove the feasibility of active flutter suppression. The first flight test was performed with a Fiat G 91/T3 which used additional control surfaces (vanes) to produce aerodynamic forces which counteract the store motion (Reference 8). In 1977, a much more challenging flight test program was launched in cooperation with the Bundesamt fur Wehrtechnik and Beschaffung (BWB) and the U.S. Air Force Flight Dynamics Laboratory (FDL). The objective of this program was to design and flight test a system for flutter suppression on an F-4F with stores. As flying test bed for this program, an F-4F aircraft of the German Air Force test center at Manching (Erprobungsstelle 61 der Bundeswehr) was chosen. The airplane was already equipped to perform flight flutter tests with stores. To

generate the necessary unsteady aerodynamic control forces, existing control surfaces (ailerons) were used. Accelerometers located on the wing provided the signals which were fed back through the existing stability augmentation system of the airplane.

Part I of this technical report documents the analysis and design of the active flutter suppression system for the F-4F aircraft with stores (Reference 9). Part II documents the ground vibration tests, the ground tests on the flutter suppression system, and the initial subcritical flight tests (Reference 10). This report (Part III) documents the flight demonstration of the active flutter suppression system. The effects of non-linearities on the flutter of the aircraft and on the design of the flutter suppression system will also he discussed in this report.

SECTION II

PREPARATION OF TEST FLIGHTS TO DEMONSTRATE ACTIVE FLUTTER SUPPRESSION IN THE SUPERCRITICAL FLIGHT RANGE

1. FLIGHT TEST PLANNING

An extensive initial flight test program was conducted in 1979. Both the safety concepts and the test methods developed for this experimental program were satisfactorily demonstrated (Reference 10). The flutter speed of the aircraft configuration without a flutter suppression system was measured at V = 600 kts. In order to demonstrate the effectiveness of the flutter suppression system, it was necessary to fly at higher speeds and lower altitudes but without reaching Mach=1.0. The Mach number restriction for these flights which had to be strictly observed was attributable to the external stores themselves which are not approved for supersonic flights, and also to the design of the flutter suppression system. This is because the aerodynamic theories, which were used to calculate the optimum control law in the flutter suppression system, are not valid in the high transonic range. Since the tests could not be carried out at the flight test center in Manching due to flight restrictions, BWB-LG IV responsible for the performarce of the flight tests and OTC E-61 decided to conduct the demonstration flights on the test site of the Nato Missile Firing Installation (NAMFI), Suda Air Force Base, on the island of Crete.

The test site is located to the north of Crete in the Mediterranean sea and offers optimum climatic conditions for low altitude flights. Problems of telemetry reception which tend to occur during low-level flights could also be resolved at this test site. A transportable telemetry station was installed on a mountain which was higher than the flight altitude. This ensured that reception of telemetry data from the transmitting antenna on the upper side of the aircraft was good.

Negotiations were conducted with Greek officials and it was agreed to conduct the tests from the 1st to the 10th of October in 1980. Both MBB and OTC E-61 had a lot of preparation to do for these flights as the test site was not equipped for this type of flight test program.

2. MODIFICATION OF FEEDBACK GAINS BASED ON GROUND TEST RESULTS

The analysis of the open-loop measurements carried out on the flutter suppression system near the flutter point in the earlier flight tests showed that the system's phase adjustment needed to be improved. The Nyquist diagram in Figure 1 illustrates that the phase of the flutter-critical external store pitch mode (5.4 - 5.6 Hz) has to be turned counterclockwise approximately 70^0 for an optimum suppression effect to be achieved. To a large extent, the phase deviation is caused by:

. The non-linear behavior of the aileron power actuator under load.

. Phase rotations, attributable to the fact that, in this transonic Mach number range, the aerodynamic forces can have major differences between the experimental values and the theoretical values.

. Phase rotations due to the concentration of non-linearities in the wing-pylon-external store combination.

For these reasons it was appropriate to recalculate the control law, taking into account all the non-linearities which had been found and which could be interpreted.

3. MODIFICATION OF FEEDBACK GAINS BASED ON FLIGHT TEST RESULTS

In order to consider the influence of the phase shift caused by the load-dependent behavior of the aileron power actuator with the aileron on the control law with greater accuracy, the control law was optimized again. To exactly describe the phase shift of the acturator with the aileron under flight load, the transfer function of the actuator measured in flight had to be introduced into the analytical model used in the optimization.

Since there are no usable measurements of this kind available, a transfer function of the actuator measured on the ground using high amplitudes was approximated and entered in the analytical model instead. It was assumed that the transfer function measured with aileron

deflections approximately eight times greater comes close to that actually occurring under flight load. Figure 2 shows an example of the dependence of the transfer function on the load when measured on the ground.

For this improved system description, the optimum feedback gains were determined again (Table 1) and the flutter calculations with the flutter suppression system were made. Figure 3 shows a comparison of the flutter calculations with and without the flutter suppression system with the modified control law. If the aerodynamic forces calculated for the aileron are introduced without modification, in theory an increase in the flutter speed of 200 kts (structural damping not taken into account) can be achieved for the selected overall gain and sensor combination III (Figure 4). As mentioned above, the unsteady aerodynamic forces in this Mach number range cannot be predicted with accuracy. Investigations concerning the YF-17 model (Reference 5) showed that the calculation procedures generally overestimated the aerodynamic forces of the aileron. If the manufacturer's data, which states that the aileron effectiveness of the F-4F is greatly reduced in the transonic range, is also taken into account a correction factor of 0.5 for the aerodynamic forces is realistic. (A factor of 0.7 was used for the YF-17 model, Reference 5).

Therefore, the damping curve of the critical mode for the corrected aerodynamic forces of the aileron has also been plotted in Figure 3. It can be seen that in this mode, a realistic increase in the flutter speed of 100 kts can be expected. In these calculations, the overall gain for the active flutter suppression system (Reference 9) was defined in such a way that at the flutter frequency the relationship between the torsion angle of the wing, θ, and the aileron deflection, $\Delta\beta$, required for flutter suppression is

$$\theta/\Delta\beta = 1.0$$

The deviation in the phase relationship of the control law caused by the difference between the aerodynamic theory and test in the transonic range cannot be completely eliminated even by a new optimization using corrected aerodynamic forces on the aileron. The previous flight tests showed that the phase rotations of the aircraft's elastic modes caused by the unsteady aerodynamic forces will be greater than predicted by calculation. These effects can only be compensated for by a universal phase correction in the flutter suppression system using test values. Thus, it was necessary to repeat the open-loop measurements on the first flight with high dynamic pressures so that the results could be used to make a final correction of the control law.

4. ADJUSTMENT OF THE MODIFIED FEEDBACK GAINS AND CHECK OF THE FLUTTER SUPPRESSION SYSTEM ON THE GROUND

Since the 20 initial flights in Manching, the F-4F flying test bed (serial No. 1126) had been refitted to some extent for use in other flight projects. For the final demonstration flights, the active flutter suppression system had to be retrofitted in the aircraft and the modified feedback gains had to be adjusted. This modification necessitated not only a functional test of the entire system but also a new structural coupling test. The structural coupling test was performed in Manching before the ferry flight to Crete. The test set-up and performance of the structural coupling test was similar to the work already described in detail in Reference 10 and thus only the new results will be shown here. Figures 5 to 9 show the results for the critical external store configuration and Figure 10 illustrates the results for the safe external store configuration (flutter stopper released). The test showed that on the ground the flutter suppression system is stable for both external store configurations. The measured feedback signals were about 30% of the input signal.

The analysis of these test results also yielded new facts and findings on the effect of non-linearities in the wing-pylon external store combination. As mentioned earlier, amplitude affects not only the resonance frequencies of the elastic modes but also the phase relations. Figure 11 illustrates this effect. The relationship of the output to

the input signal and the phase of the maximum response signal of the bending mode were taken from the structural coupling test and plotted versus the excitation amplitudes. This diagram shows clearly that the phase relation of this mode is dependent on the amplitude of excitation. One can safely assume that this will also apply to the flutter-critical mode. The magnitude of this nonlinearity under aerodynamic load however, is unknown.

After the first test flight on Crete with high dynamic pressures, the feedback gain had to be corrected again due to the non-linearities which could not be determined mathematically. This necessitated a new structural coupling test. Figures 12 and 13 show the results of this structural coupling test with two levels of excitation. Just like the previous tests, the Nyquist diagrams show that there is a nonlinear behavior and that there is no detrimental coupling of the flutter suppression system with the elastic modes of the aircraft.

SECTION III

FLIGHT TESTS TO DEMONSTRATE THE ACTIVE FLUTTER SUPPRESSION SYSTEM

1. SUMMARY OF THE FLIGHT TESTS

During the final test phase, a total of six flights were performed. The first flight (No. 246/22) was performed in Manching solely for inspection purposes since the aircraft had been retrofitted with the active flutter suppression system. Flight No. 247/23 through 251/27 were performed on Crete. The last flight, No. 251/27, was flown without external stores to investigate the influence of external stores on the aerodynamics of the aileron.

A summary of the test points flown and the most important test data of flights 247/23 through 251/27 has been compiled in Table 2. All the given flight data such as speed, altitude, and Mach number are instrument readings made by the pilots.

2. FLIGHT PROGRAM

The flight program for the demonstration of the flutter suppression system involved:

. Checking of safety devices (flutter stopper);

. Open-loop measurements to check the newly adjusted feedback gain

. Flight tests with closed-loop control in the supercritical speed range.

To keep the non-linearity effects to a minimum, only very small aileron deflections were permitted (amplitude switch at 25%, which corresponds to aileron deflection of $\pm 0.2^{0}$ up to about 5 Hz) for excitation during open-loop measurements (test program 1, Figure 14) and when applying the test signal as a perturbation signal in the closed loop measurements (test program 7). Stick jerks were used in addition to tests with a defined excitation through the aileron.

A total of 21 test points were flown on the five test flights in Crete. Because of the high dynamic pressures required, the flights, and consequently the test durations, were very short. The individual test points had to be flown quickly and with precision.

Extensive telemetry monitoring was necessary for these test flights in the critical and supercritical speed ranges. For this reason, a transportable telemetry station was installed at a location with good reception at the periphery of the test site. All the important sensor and control signals were monitored during the flight test. Some damping evaluations were made by MBB on an HP 5451B computer during the flight.

Except for a coupling effect of the active flutter suppression system with the pitch damper of the flight control system which led to a large but damped rigid-body vibration of the aircraft, the flight tests concluded with no significant problems. These coupling effects will be discussed in detail later in the report.

3. RECORDING AND EVALUATION OF TEST DATA

All signals from the sensors in the flutter suppression system (Figure 15, the control signals from the control electronics, the frequency signal generator, and all acceleration signals for monitoring the aircraft's flutter modes were recorded on tape. Reference 11 contains a detailed list of all data measured in flight and the method of recording. The signals used for evaluating the tests of the flutter suppression system are contained in Table 3. These signals were monitored by the telemetry station during the flight. At the same time the accelerometer signals ZAL/ZAR from the external stores were fed directly into the HP 5451 B computer, thus monitoring the damping during the flight.

After the flight tests, all the other important sensor and control signals were evaluated from tape. For the evaluation of the damping from these signals, filter correlation methods were used, as described in Reference 12. Figures 16 through 25 show several examples of various acceleration signals that were evaluated. In some cases, better results

were obtained from using autocorrelation methods than cross correlation methods.

In order to achieve reliable damping values, all the sensor signals were analyzed. The acceleration signals from the external stores provided the most reliable damping evaluations. The signals from the sensors on the wings were highly contaminated with noise, and it was difficult to determine the effectiveness of the flutter suppression system from these signals. The originally planned method of demonstrating the effectiveness of the flutter suppression system by briefly switching the system off and then evaluating the damping could not be used. The pulses from switching on and off, as well as the tests with stick jerks, excited the lightly damped rigid-body pitch mode of the aircraft.

The demonstration of the active flutter suppression system was performed as follows: The aircraft with its active flutter suppression system is regarded as a closed system. If this system is excited by means of the ailerons as is the case in the closed-loop measurements in test program 7, the damping of the aircraft with a suppression system can be determined from the responses. The effectiveness of the system can be determined exactly by comparing the damping trends of the flutter-critical mode measured with and without an active suppression system.

4. DISCUSSION OF TEST RESULTS

The effectiveness of the active flutter suppression system was clearly demonstrated in the flight tests on Crete. The improved Control Law III (Table 1) enables the flutter speed to be increased by approximately 100 kts, as illustrated by the extrapolation of the measured damping trend in Figure 26. This increase in flutter speed agrees very well with the values predicted by analysis (Figure 3) when the corrected aerodynamic forces of the aileron are used. The main objective of the flight tests, to demonstrate the active flutter suppression system on a divergent flutter mode (exponentially increasing amplitudes), was not attained during these flights with high dynamic pressures. The non-linearities in the wing-pylon-external store

combination caused a limited amplitude flutter (damping = 0% g). However, it was demonstrated that a significant increase in the fluter speed was provided by the active flutter suppression.

Previous tests had revealed that due to the non-linearities, the open-loop and closed-loop tests could only be conducted with small amplitude excitation. If too large an excitation is used, the tightening torque of the adjustment bolt shown in Figure 27 is no longer sufficient to keep the pylon firmly attached to the wing. This causes the roll stiffness of the pylon to change and flutter no longer occurs. To avoid this effect, the maximum excitation amplitudes were restricted to 25% ($\pm 0.2^{o}$ aileron deflection at 5.3 Hz).

The tests clearly show that the flutter suppression system can increase the damping of the flutter-critical store pitch mode by approximately 5%. It is very difficult to estimate the aileron deflections necessary to do this since, a perturbation signal was superimposed on the control signal for these tests. The necessary aileron deflections were estimated at $\pm 0.2^{o}$. This would mean that aileron rates of only 4.5^{o}/sec are required for flutter suppression in level flight. However, it must be borne in mind that this does not include the reserves necessary for flight maneuvers, gusts, and turbulence.

This is, however, a very important result with regard to the concept of future flutter suppression systems. It confirms that in the event of external store flutter, the rates of the state-of-the-art actuators may be sufficient. The tests also confirm that, due to the small aileron deflections required by the flutter suppression system, the flight control system and the flutter suppression system can in principle both use the same control surfaces, provided that they are suitably located. Furthermore, the tests have confirmed that it is possible to optimize the active flutter suppression system by using a linear, mathematical model of the aircraft. The influence of the non-linearities could, to some extent, be taken into account in the calculation or could be compensated for by data measured during flight.

The safety concept developed for this experimental program was also verified in these flight tests. The flutter stopper in the external stores proved very successful. A damping value of approximately 4.2%g for the flutter-critical store pitch mode was provided at V = 600 kts with the movable weights of the flutter stopper in the safe position (weights in the critical position, damping = 0%, limited-amplitude flutter). Even a pessimistic extrapolation of the suppression curve of the store pitch mode (weights of flutter stopper in safe position) in Figure 28 shows that the flutter stopper is effective up to V = 750 kts. For flight tests with up to V = 640 kts, a sufficiently large safety margin was maintained with respect to the flutter point of the aircraft with an active flutter suppression system.

5. INTERACTION BETWEEN THE FLUTTER SUPPRESSION SYSTEM AND THE FLIGHT CONTROL SYSTEM

As discussed earlier, during the tests using stick jerk excitation there was a coupling between the flutter suppression system and the flight control system. After excitation with stick jerks, a lightly damped pitch oscillation of the rigid aircraft occurred at a frequency of 1.5 Hz. This oscillation caused deflections of the ailerons and the stabilizer. According to the pilots, the oscillation decayed rapidly once the stick had been released. This behavior indicates that the pilot is included in the control loop (PIO = Pilot Induced Oscillations). Figures 29 and 30 show time histories of this oscillation. Acceleration occurring at the pilot's seat amounted to ± 0.5 g. The amplitudes of this pitch oscillation of the entire aircraft - which did not occur until V > 600 kts - are dependent on speed and are lightly damped. Evaluation of the recorded data indicated a damping of 3% g at V = 620 kts.

The fact that coupling occurred between the two systems shows that the flight control system and the flutter suppression system must be strictly separated. A band-pass filter had been installed in the flutter suppression system which at 1.5 Hz reduced the amplitudes by approximately 7 dB. This filter was obviously insufficient at high speeds. The problem of decoupling the systems must be given closer consideration in future designs.

6. POSSIBILITY OF USING AN ACTIVE FLUTTER SUPPRESSION SYSTEM FOR A FLIGHT FLUTTER TEST

In addition to being used as a flutter suppression system, the system can also be used in flight flutter tests. As in the open-loop measurements, the excitation of an aircraft by its own control surfaces had proved effective in the flight flutter test (Reference 1). This method of excitation can also be used at any time with a flutter suppression system connected in an open loop.

Flight flutter tests in which the flutter point is approached are very risky. On the other hand, for a given aircraft/store configuration to be certified, the damping trends of the flutter-critical modes must be explored in flight until a safe extrapolation of the flutter speed is possible. If a flutter suppression system is used in the flight flutter test, the test has a much lower risk factor. This method has the following advantages:

. During tests in the critical range, the flutter suppression system can be switched on as a safety device.

. The flutter point of the critical mode can be determined directly (this procedure has already been tested in the wind tunnel (Reference 1).

One further possibility is to calculate the open loop response from closed-loop measurements taken in the critical flight range and to determine the damping of the aircraft from the open-loop response. This procedure is the least risky as the measurements are conducted on a <u>stable</u> aircraft with an active flutter suppression system. However, the conversion of closed-loop measurements to open-loop measurements has some problems. For these tests, unknown interference must not be superimposed upon the defined input. During flight tests, however, there are always unknown interferences superimposed (turbulences, gusts). Thus, test conditions must be created in which these unknown interferences are kept small as compared to the defined input. This was not the case in the flight tests on Crete as the excitation had to be kept very small due to the non-linear effects. For this reason, it was

not possible to make useful calculations from the closed loop back to the open loop for critical and supercritical flight speeds.

7. INVESTIGATION OF THE INFLUENCE OF NON-LINEARITIES ON THE DESIGN AND TESTING OF THE FLUTTER SUPPRESSION SYSTEM

In the design of an active flutter suppression system, it is expedient to start from the linear mathematical model which is also used in the flutter analysis. The flutter suppression system itself is also assumed to be linear. This method has proved effective for optimizing the control law. A simple linear system model offers flexibility in the design phase.

It is possible to estimate certain non-linear effects by parameter analysis. The important non-linearities to be considered during the design of an active flutter suppression system were shown in this flight program to be:

- Concentrated structural non-linearities;
- Non-linearities of the actuators;
- Non-linearities of the unsteady aerodynamic forces in the transonic range.

In the case of concentrated structural non-linearities, which in the F-4F occur in the wing-pylon-external store combination, both the frequency and the phase of an elastic mode are dependent on load. During control law optimization for the flutter suppression system, this control law is optimized for only one amplitude and one speed. If high amplitudes occur during the flight, from gusts for example, the control law's effectiveness can be reduced substantially due to the phase shifts. Structural damping, which is a distributed non-linearity (friction at rivets in the structure), can be neglected in the design of a flutter suppression system.

The actuators have a strong load-dependent transfer function in the frequency range required for flutter suppression. However, the transfer functions have to be considered during the optimization of the control laws. Very large input signals can force the actuator into saturation

and it then completely loses the phase reference, unlike the load-dependence. This non-linearity is very dangerous for the flutter suppression system because when this effect appears, the flutter suppression system can be rendered ineffective.

If large impulses occur in the transonic range, the theories on unsteady aerodynamic forces, which were used in the control law optimization, are not valid. The control law is also no longer valid if flow separation, buffeting, etc. occurs.

In order to learn more about these non-linear effects and their influence on the design of active flutter suppression systems, the flight test results were reanalyzed with this in mind.

3. EVALUATION OF NON-LINEAR FLIGHT TEST RESULTS

The flight test results were carefully analyzed, keeping in mind the considerations mentioned in the previous paragraphs. The findings from the tests in Manching were used as much as possible for the flight tests on Crete. The influence of the load-dependent transfer function of the actuators was discussed in Section II.2. An attempt was made to estimate, from the structural coupling test and in-flight open-loop measurements, the influence of the concentrated structural non-linearities with respect to frequency shift and phase relationship as a function of load and amplitude. This influence was taken into account in the correction of the control law.

Using the knowledge about the non-linearities obtained during the initial flight test in Manching, the excitation amplitude was limited to 25% of the maximum value for investigations using test programs 1 and 7 (Figure 14) on Crete. The frequencies of the wing bending and the roll and pitch modes of the external stores were analyzed for each test point and compared with the values already available from flights at Manching to ensure that the test conditions were similar.

Figure 31 shows the test data from the flights on Crete and confirms the trend found earlier. To complete these diagrams, some values from closed-loop measurements were used. However, this is permitted for investigating non-linearities which occur as frequency jumps, since the flutter calculations with an active flutter suppression system (Figure 3) show that there are only small continuous frequency changes in the velocity range of interest.

Figure 31 shows that frequency jumps did not occur in the roll mode at 25% excitation. This means that the demonstration flights were conducted with a system capable of flutter and that the results are comparable to those from previous flight tests and also with the calculations. Figure 32 shows the frequencies plotted versus speed for the open-loop and closed-loop measurements. The established trends are comparable to the calculations and do not show any frequency jumps, which would indicate a concentrated structural non-linearity.

It is very difficult to analyze the in-flight open-loop measurements with regard to the influence of non-linearities, as several non-linear effects have to be considered at a time. The number of tests was too small to obtain enough information to analyze all significant non-linear effects. Thus, attention must be drawn to one particularly serious effect. The comparison of two open-loop measurements in Figures 33 and 34 clearly shows the strong amplitude dependence, found in the structural coupling test. For excitation with 50% of the maximum excitation amplitudes, essentially only the wing bending mode is excited (Figure 33). Due to the strong damping and the proximity of adjacent frequencies, the store pitch mode can no longer be separated from the bending mode. The picture is quite different when the excitation is 17% of the maximum excitation (Figure 34). Despite the bad signal-to-noise ratio, this evaluation allows a separation of the two modes. A global phase rotation can be found between the two Nyquist diagrams. However, it is very difficult to interpret this effect. The phase shift consists of components resulting from the aileron system under load and the transonic aerodynamics (M = 0.91).

These effects have to be given very careful consideration in the design of an active flutter suppression system. For example, if the structure is additionally excited by gusts in the supercritical speed range and if large amplitudes of the structure are induced, the phase shifts can become so large that the control law becomes ineffective. This can be catastrophic for the aircraft, since the flutter suppression may no longer be capable of stabilizing the structure.

SECTION IV

CONCLUSIONS

This report completes the joint U.S./German effort to develop and flight test an active flutter suppression system on an F-4F aircraft with external stores. The flutter suppression system was designed (Reference 9) and integrated into the roll channel of the flight control system. Existing control surfaces (ailerons) were used as the active control surfaces, and wing-mounted accelerometers provided the feedback signals for the flutter suppression system. Modified actuators were used that had better high frequency characteristics than the standard F-4 actuators. A safety concept (flutter stopper), which increases the flutter speed in the event of a system failure by mechanically moving masses in the external store was developed and successfully tested.

The control law was optimized by means of a linear mathematical model, which was corrected based on test data. Difficulties in the design of the control law were experienced because of non-linear effects of the actuator, the structural non-linearities of the wing/pylon/store combination, and the transonic aerodynamics. The non-linearities also caused considerable problems in the ground andflight tests (Reference 10).

Due to the high degree of amplitude-dependence, the flight tests could only be conducted using small excitation forces. If the amplitude of excitation was too large, the frequency of the flutter critical modes changed, and flutter no longer occurred. For the low excitation, a limited-amplitude flutter occurred.

The active flutter suppression system was successfully demonstrated. At high dynamic pressures, there was some coupling of the flutter suppression system with the aircraft rigid-body mode. The flutter mode was well damped with the active flutter suppression system operating. The aircraft was flown 45 knots above the passive flutter speed, and extrapolated data showed a possible 100 knot increase in speed with the active flutter suppression system.

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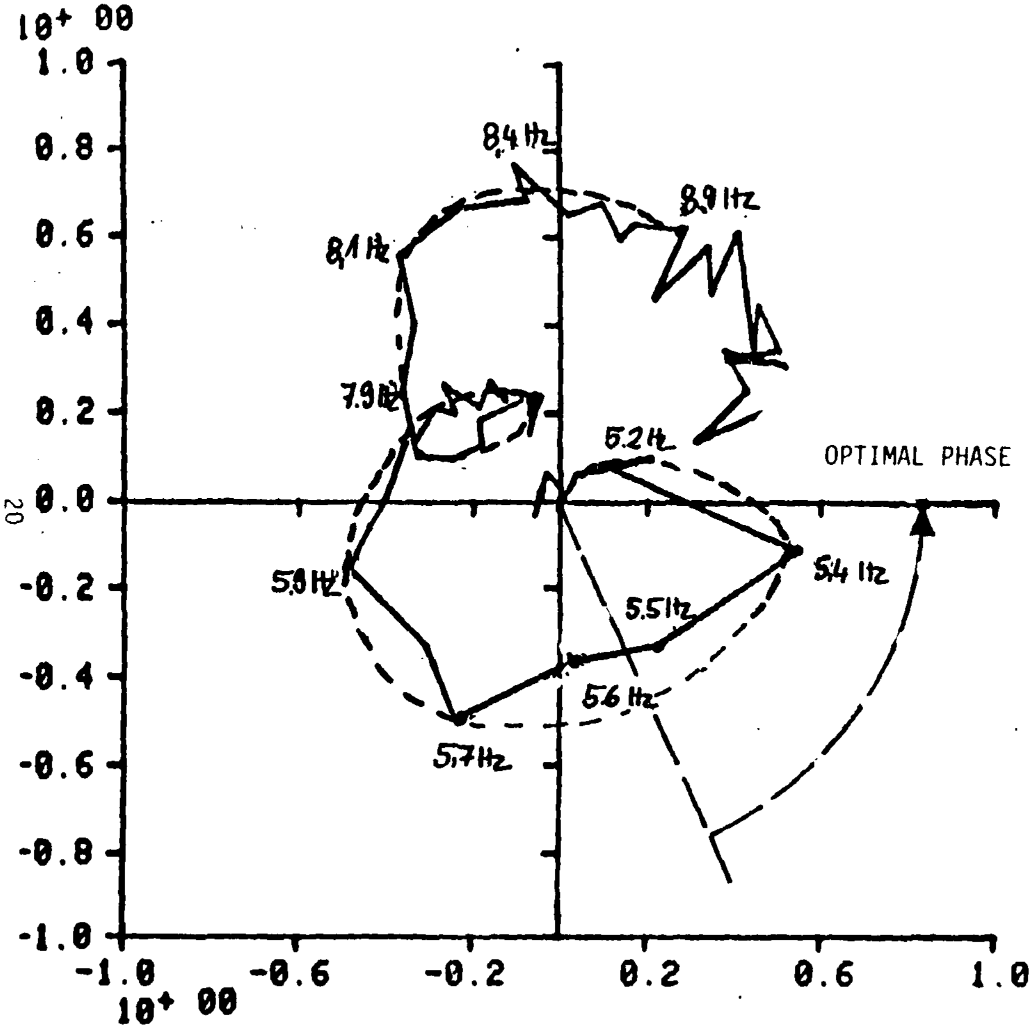
F-4F 72-1126 FLIGHT 191/17 580 KIAS, 4800 FT, MA 0.94 LBFK CRIT



OPEN LOOP MEASUREMENT

$$F_{(i\omega)} = \frac{X_A}{X_E} = \frac{KONTR-R}{FL-SIN}$$

INPUT: FREQUENCY SWEEP

EXCITATION LEVEL: 17 %

Figure 1. In-Flight Open Loop Test, M = 0.94

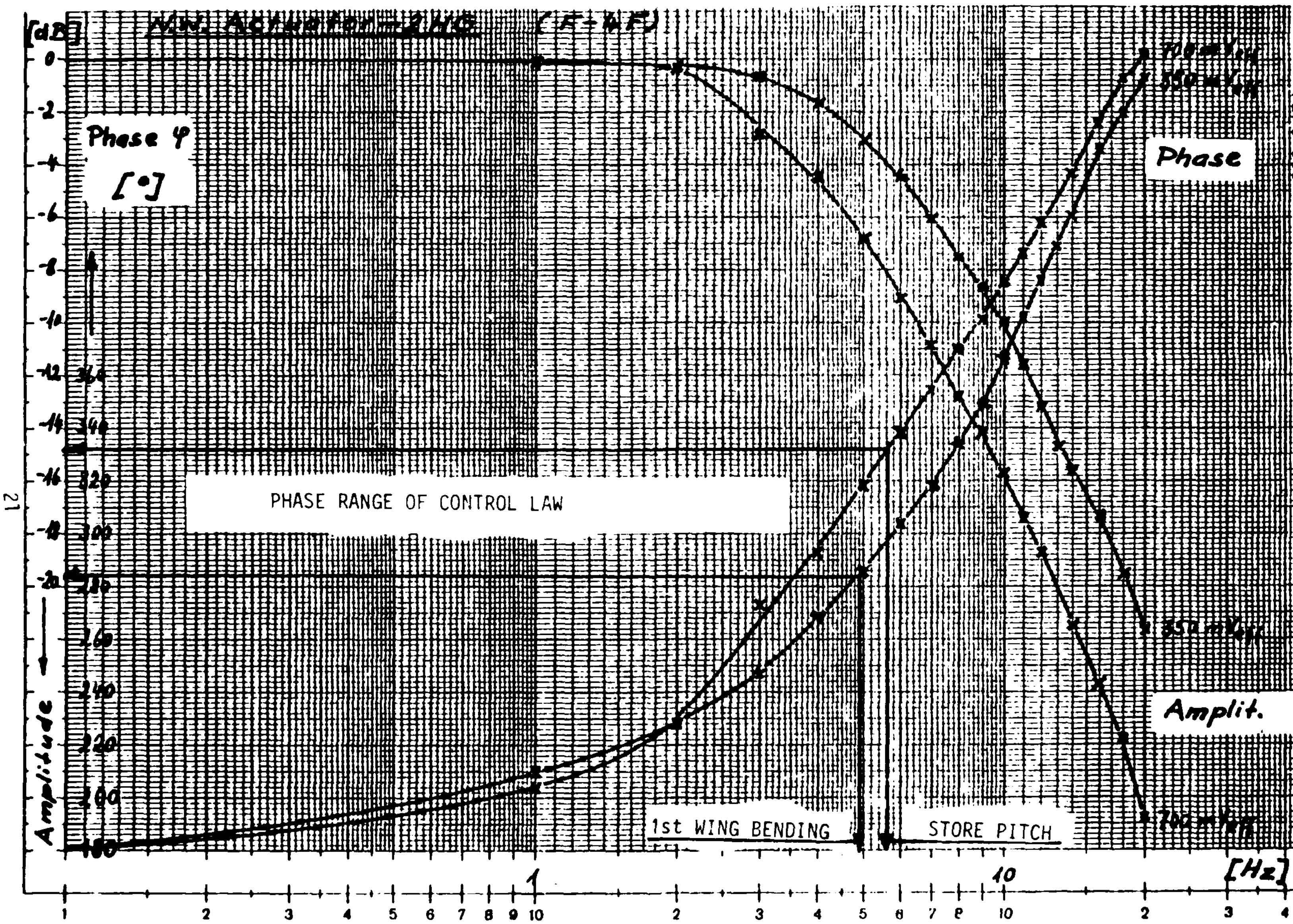


Figure 2. Transfer Function of the Roll Channel for Various Aileron Angles

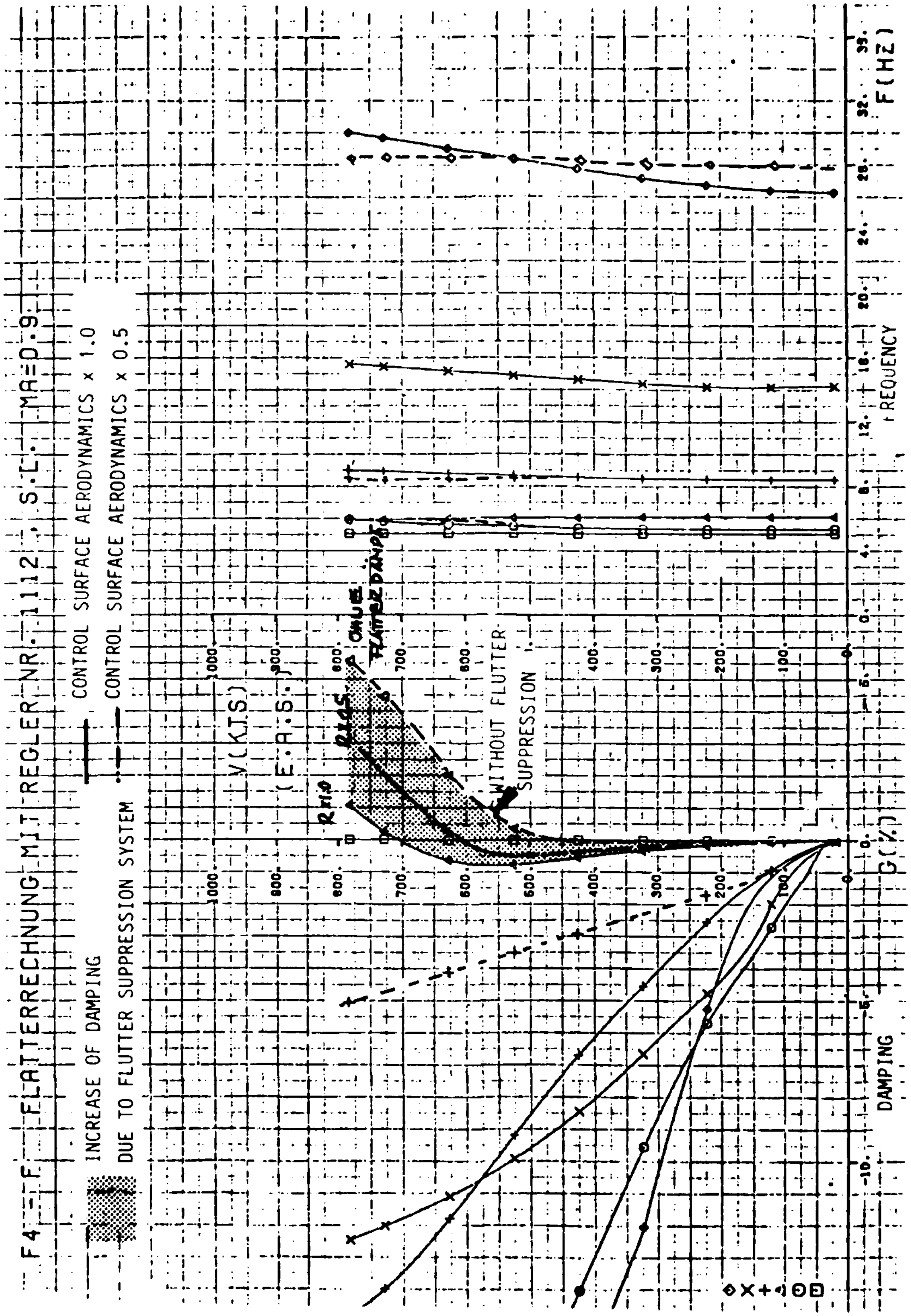
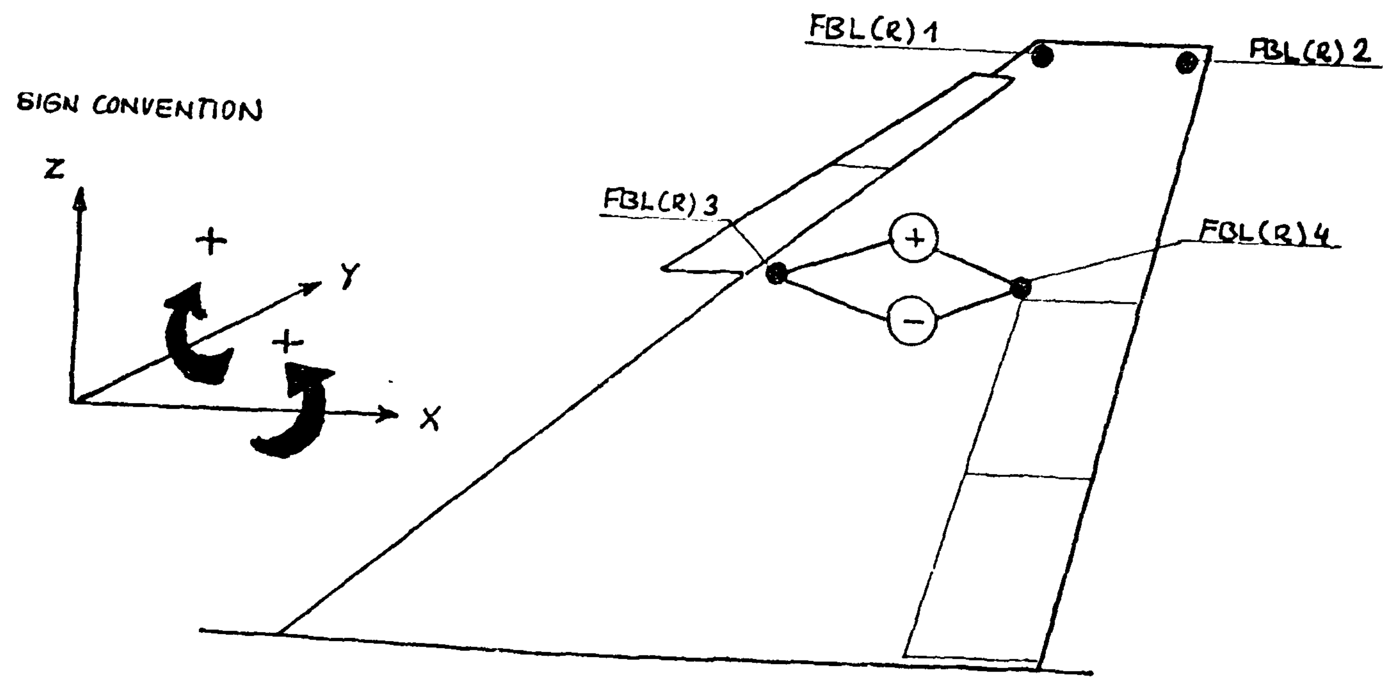


Figure 3. Flutter Calculation with Flutter Suppression System
(Modified Control Law)



SENSOR COMBINATION III

FLÜGEL BIEGUNG WING BENDING	φ	$1/2 \iint$ (FBL(R)3 + FBL(R) 4
AUSSENLAST NICKEN STORE PITCH	Θ	$\iint$ (FBL(R)3 − FBL(R) 4

Figure 4. Definition of Sensor Combinations for the Active Flutter Suppression System

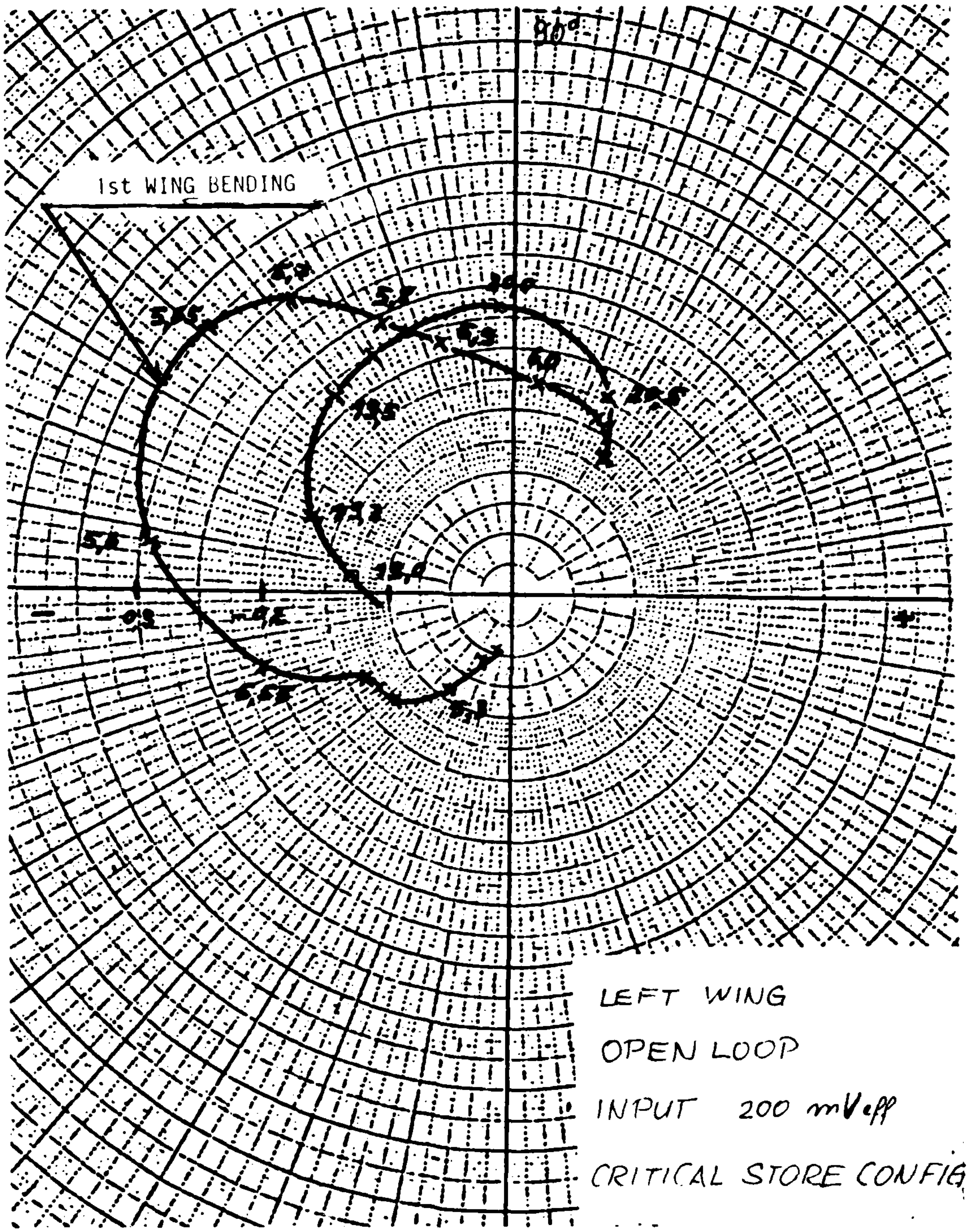


Figure 5. Structural Mode Coupling Test with Critical Store, Left Wing

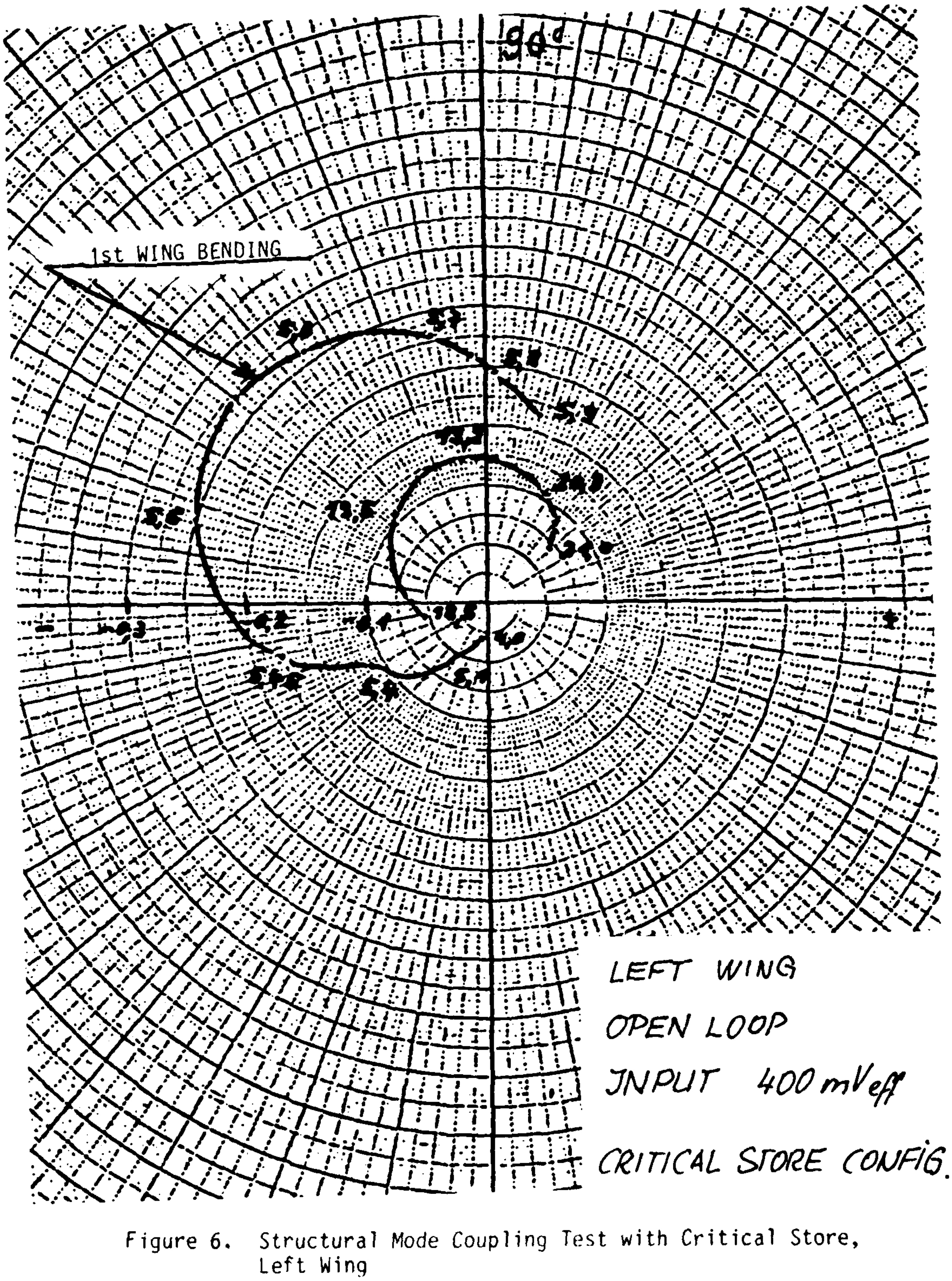


Figure 6. Structural Mode Coupling Test with Critical Store, Left Wing

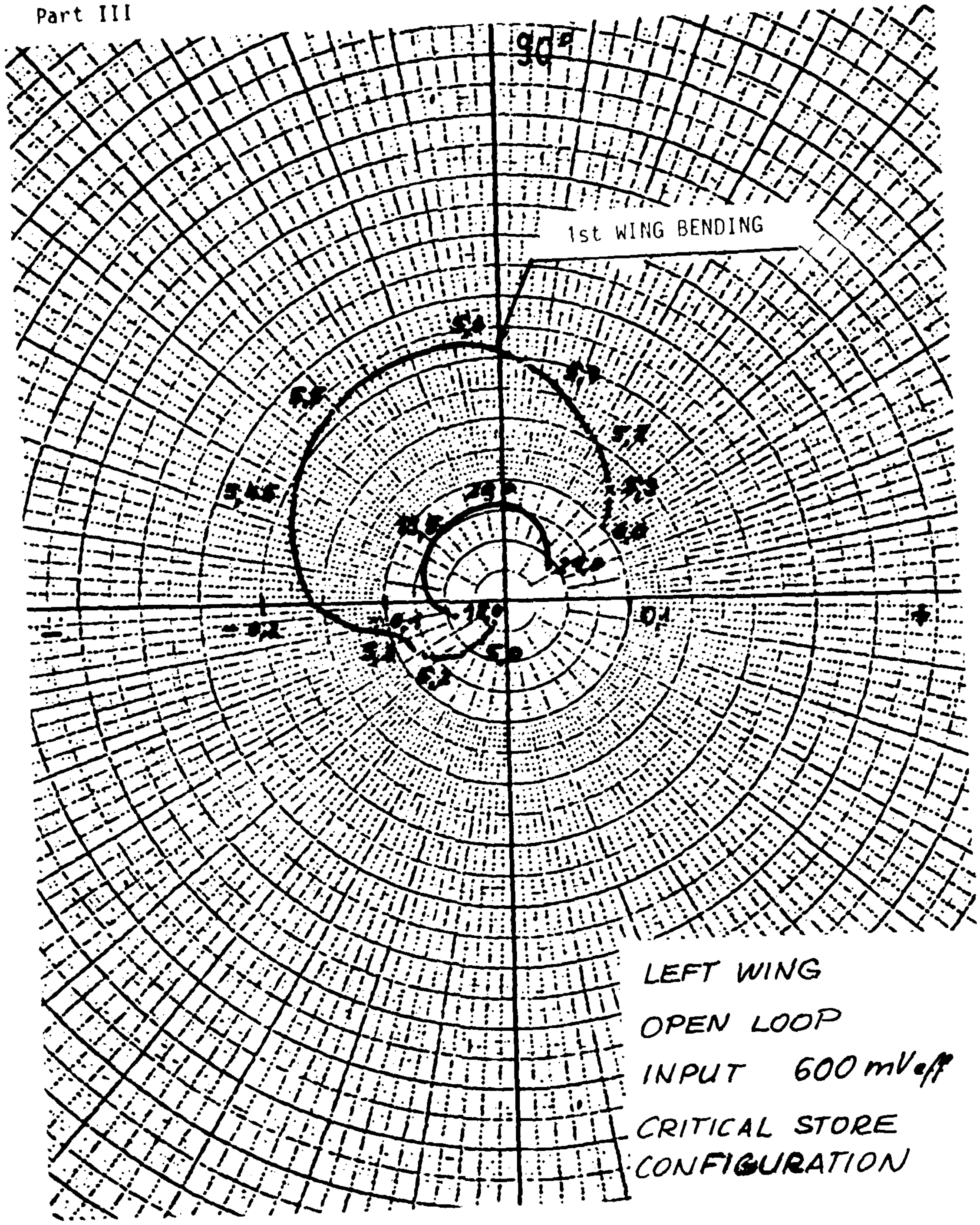


Figure 7. Structural Mode Coupling Test with Critical Store, Left Wing

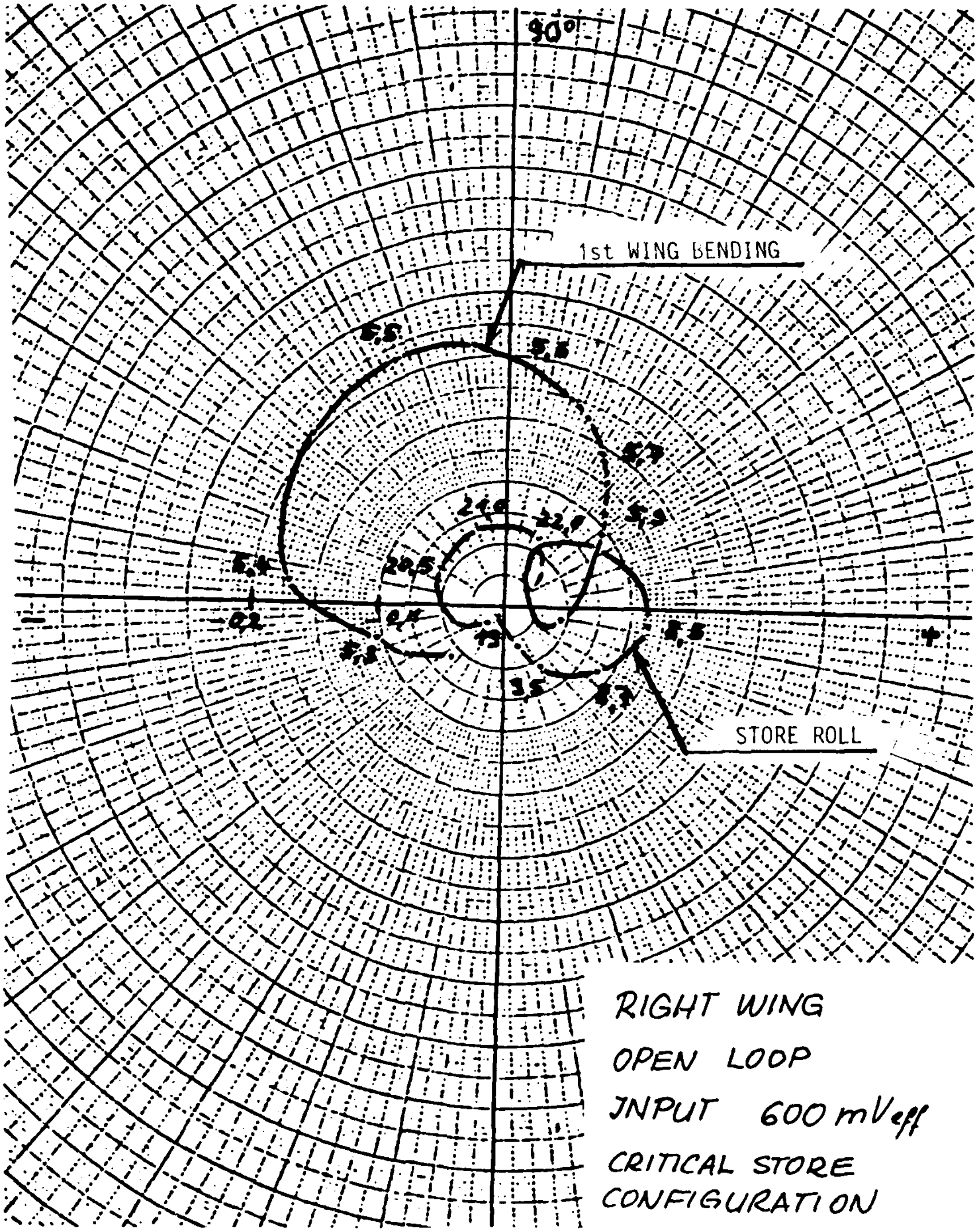


Figure 8. Structural Mode Coupling Test with Critical Store, Right Wing

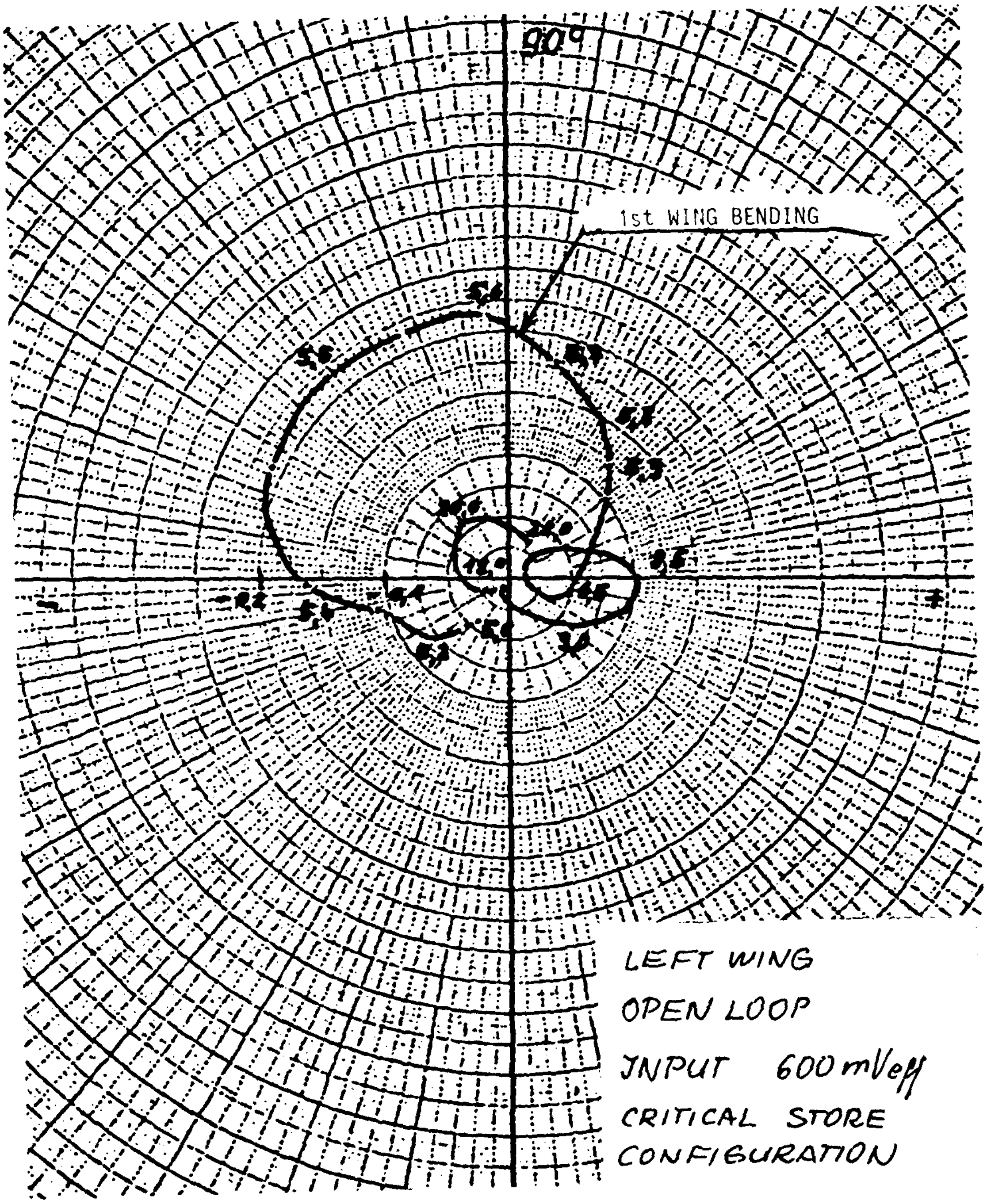


Figure 9. Structural Mode Coupling Test with Critical Store, Right Wing

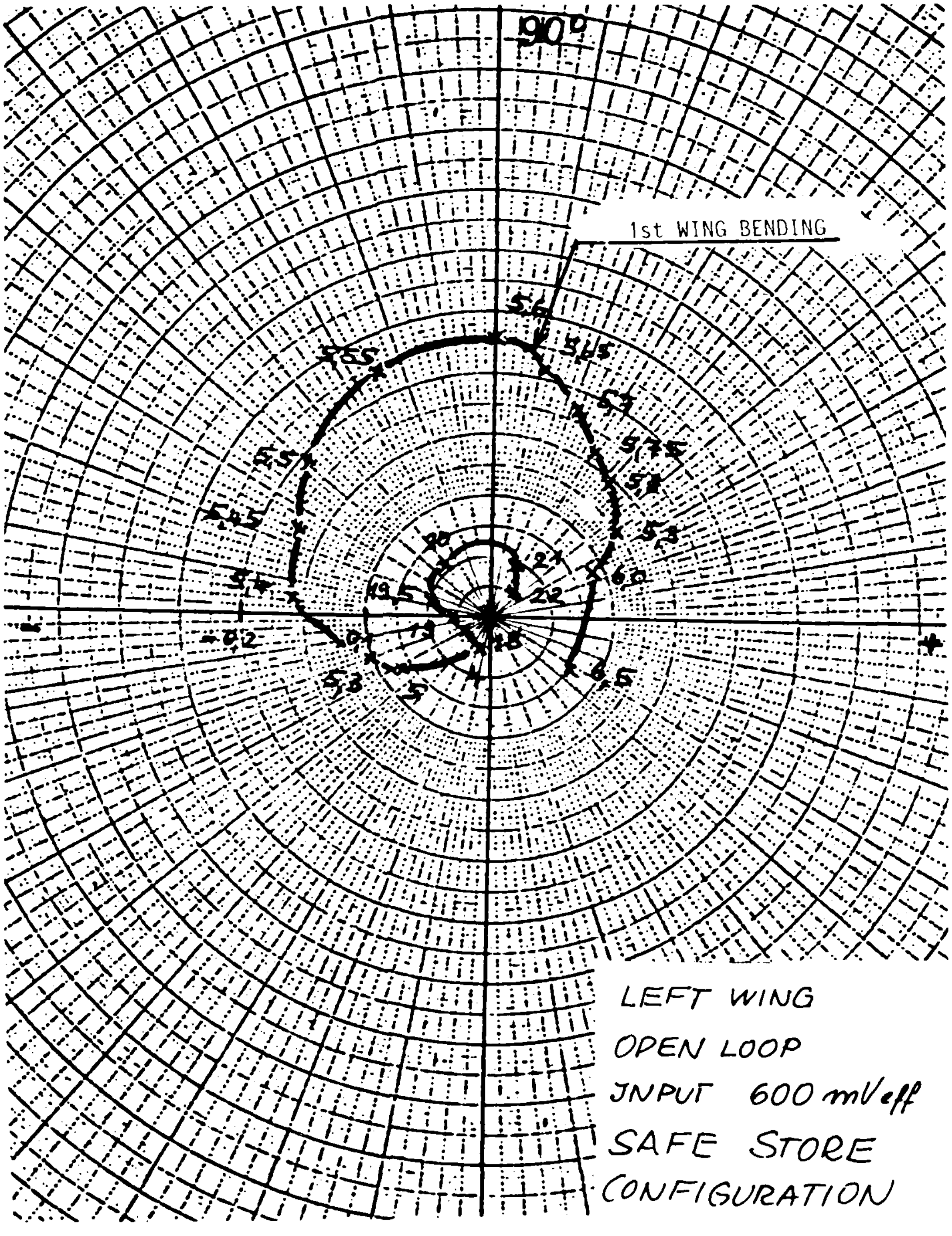


Figure 10. Structural Mode Coupling Test with Safe Store, Left Wing

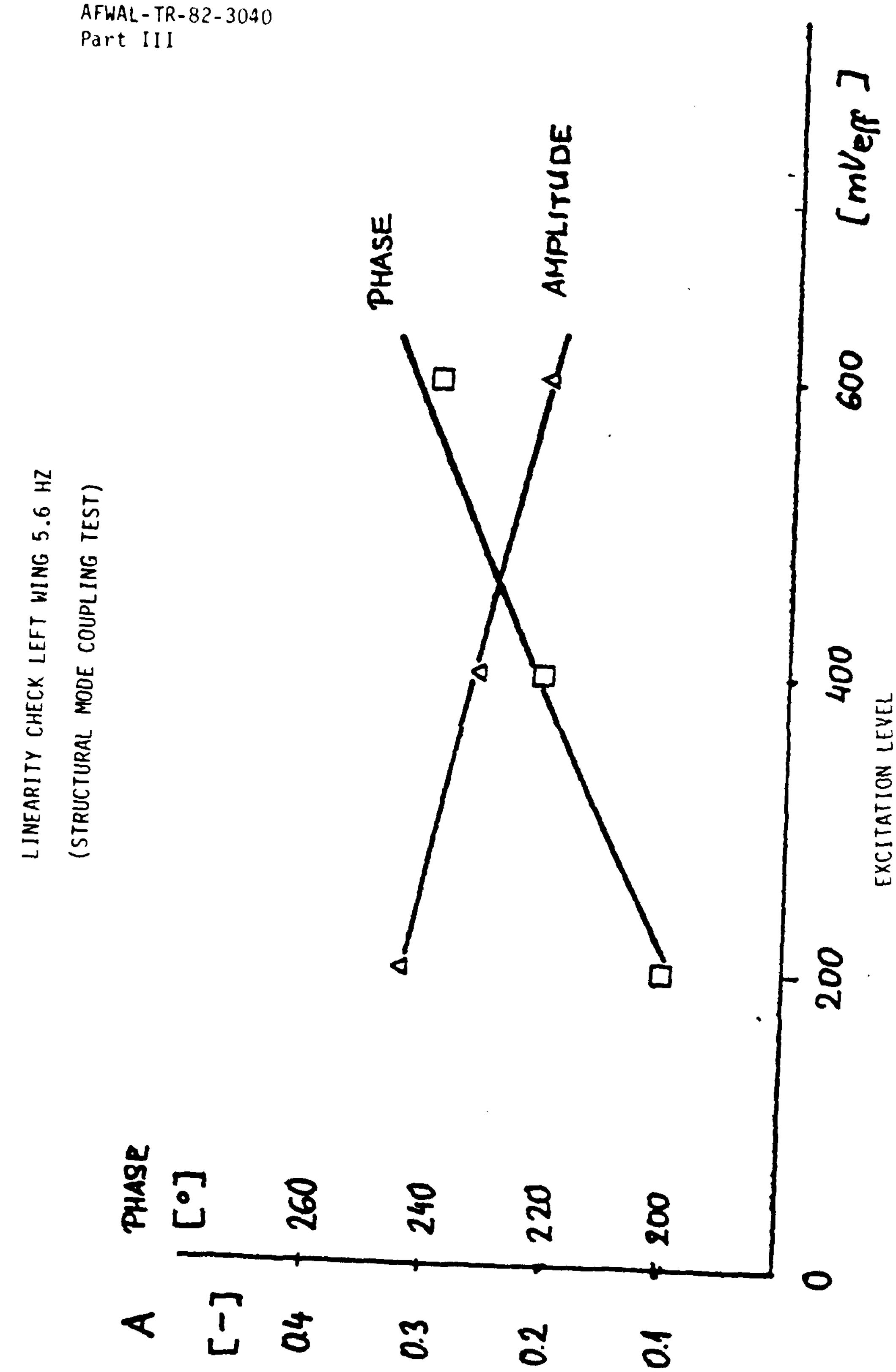


Figure 11. Linearity Check for the Flutter Suppression System

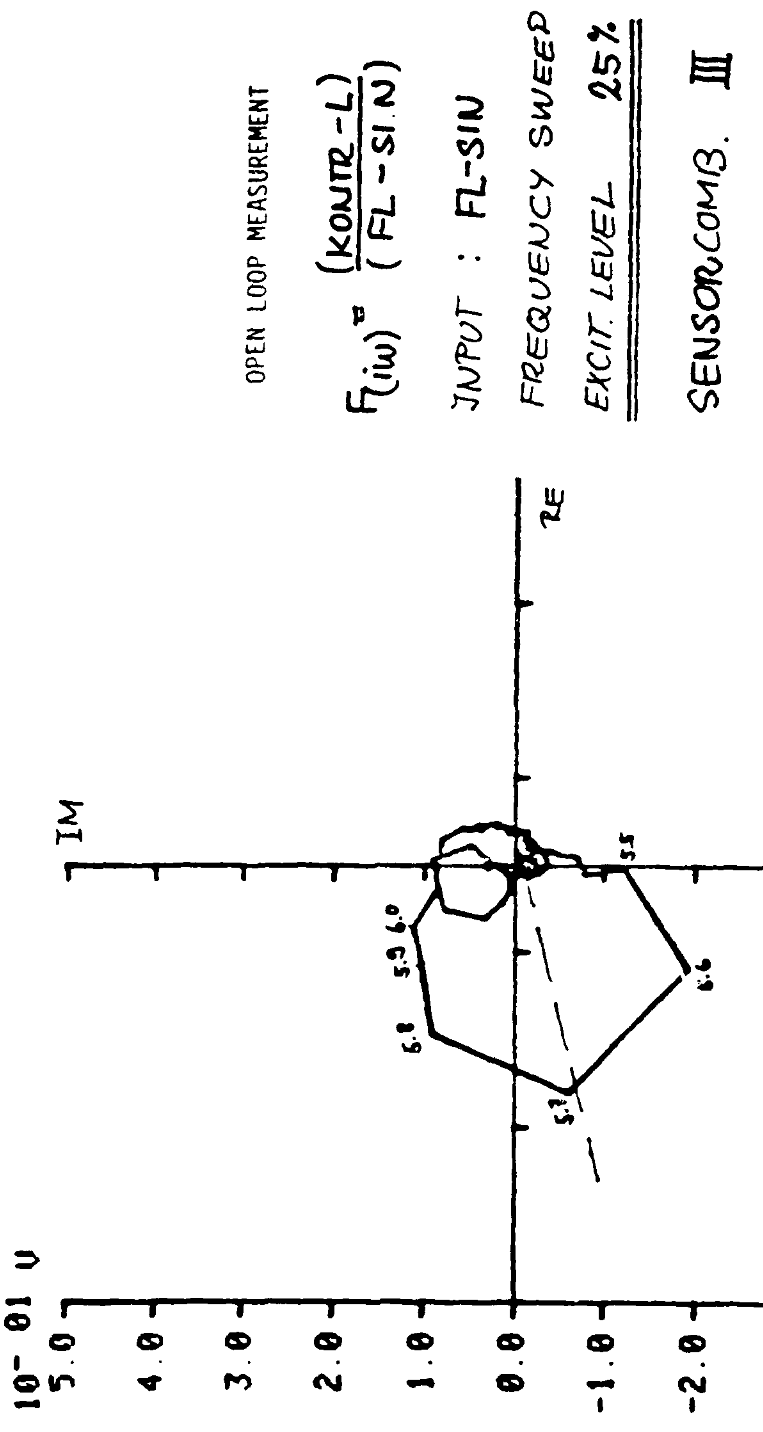


Figure 12. Structural Mode Coupling Test with Critical Store (Modified Control Law)

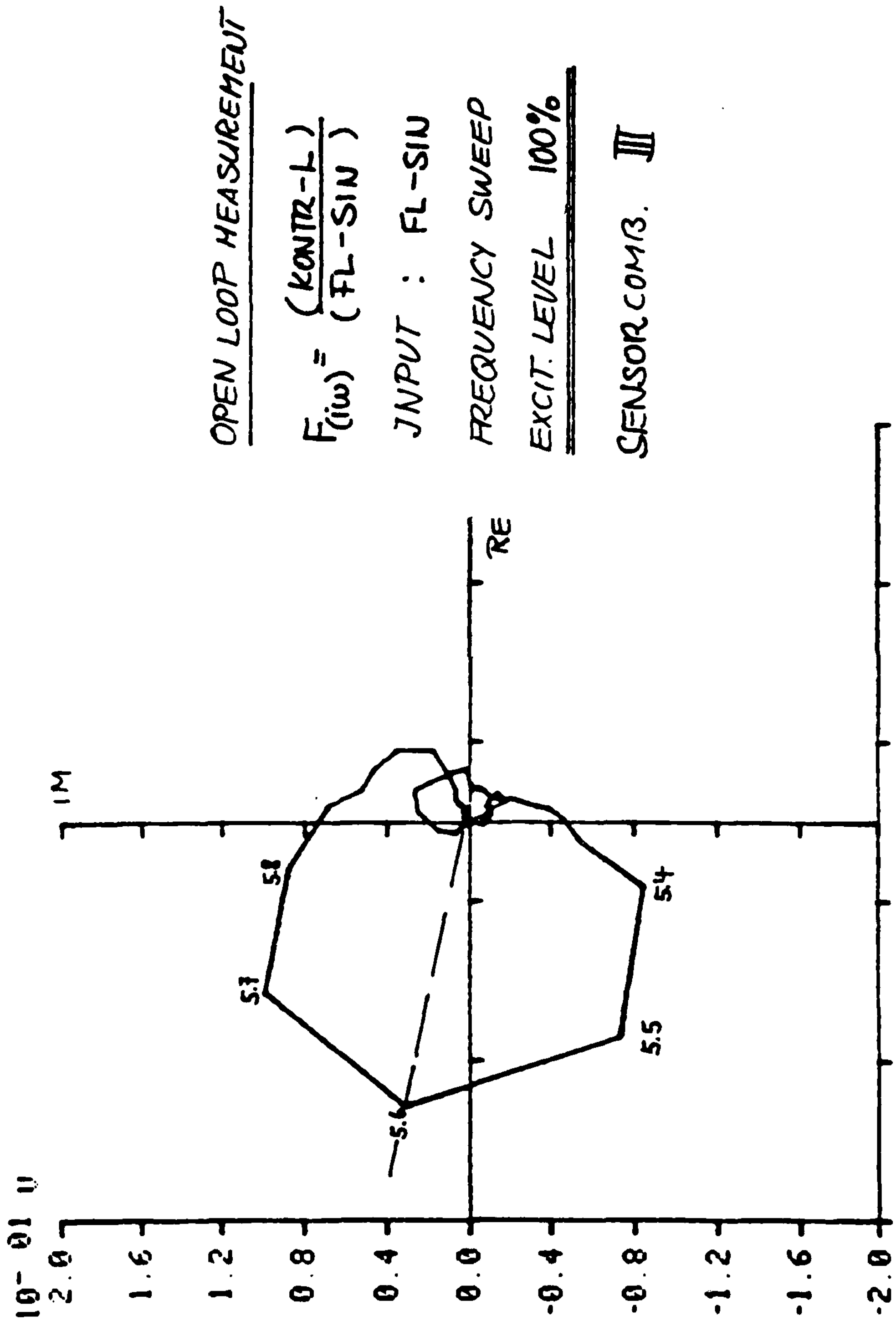


Figure 13. Structural Mode Coupling Test with Critical Store (Modified Control Law)

TESTPROGRAMM / TEST PROGRAM F-4F W/N 1126		
NR. / NO.	FUNKTION / FUNCTION	
	RE. FLÜGEL / RIGHT WING	LI. FLÜGEL / LEFT WING
1	OFFENKREIS M. GLEITFREQUENZ OPEN LOOP W. FREQUENCY SWEEP	OFFENKREIS M. GLEITFREQUENZ OPEN LOOP W. FREQUENCY SWEEP
2	GLEITFREQU./FREQUENCY SWEEP	DÄMPFUNG/DAMPING
3	DÄMPFUNG/DAMPING	GLEITFREQU./FREQUENCY SWEEP
4	AUTOMATISCHE ERREGUNG AUTOMATIC EXCITATION	AUTOMATISCHE ERREGUNG AUTOMATIC EXCITATION
5	DÄMPFUNG/DAMPING	AUTOMATISCHE ERREGUNG AUTOMATIC EXCITATION
6	AUTOMATISCHE ERREGUNG AUTOMATIC EXCITATION	DÄMPFUNG/DAMPING
7	GESCHL. KREIS M. GLEITFREQUENZ CLOSED LOOP W. FREQU. SWEEP	GESCHL. KREIS M. GLEITFREQUENZ CLOSED LOOP W. FREQU. SWEEP
8	DÄMPFUNG/DAMPING	DÄMPFUNG/DAMPING

Figure 14. Test Program for the Flight Test of the Flutter Suppression System

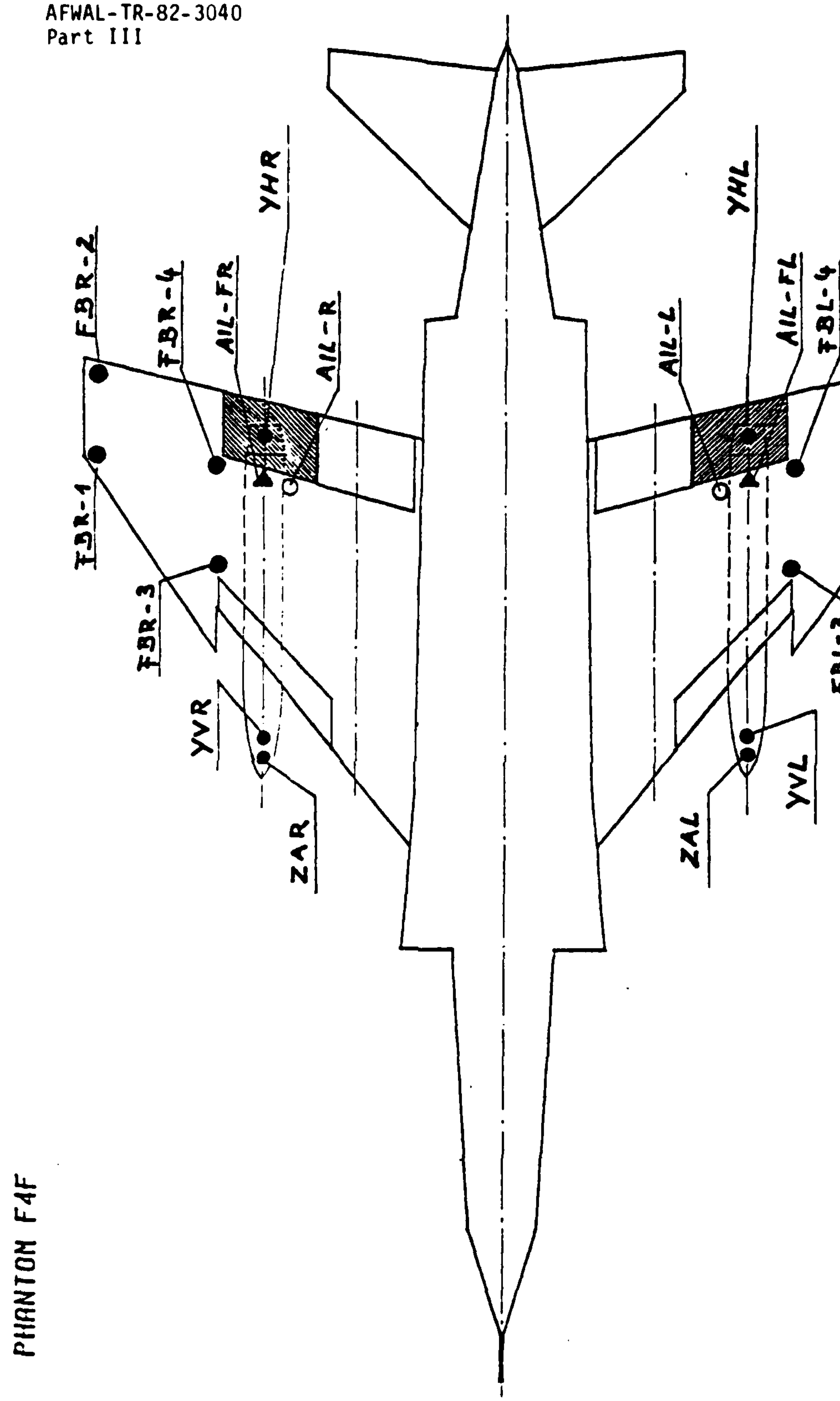


Figure 15. Sensor Installation for the Flight Test

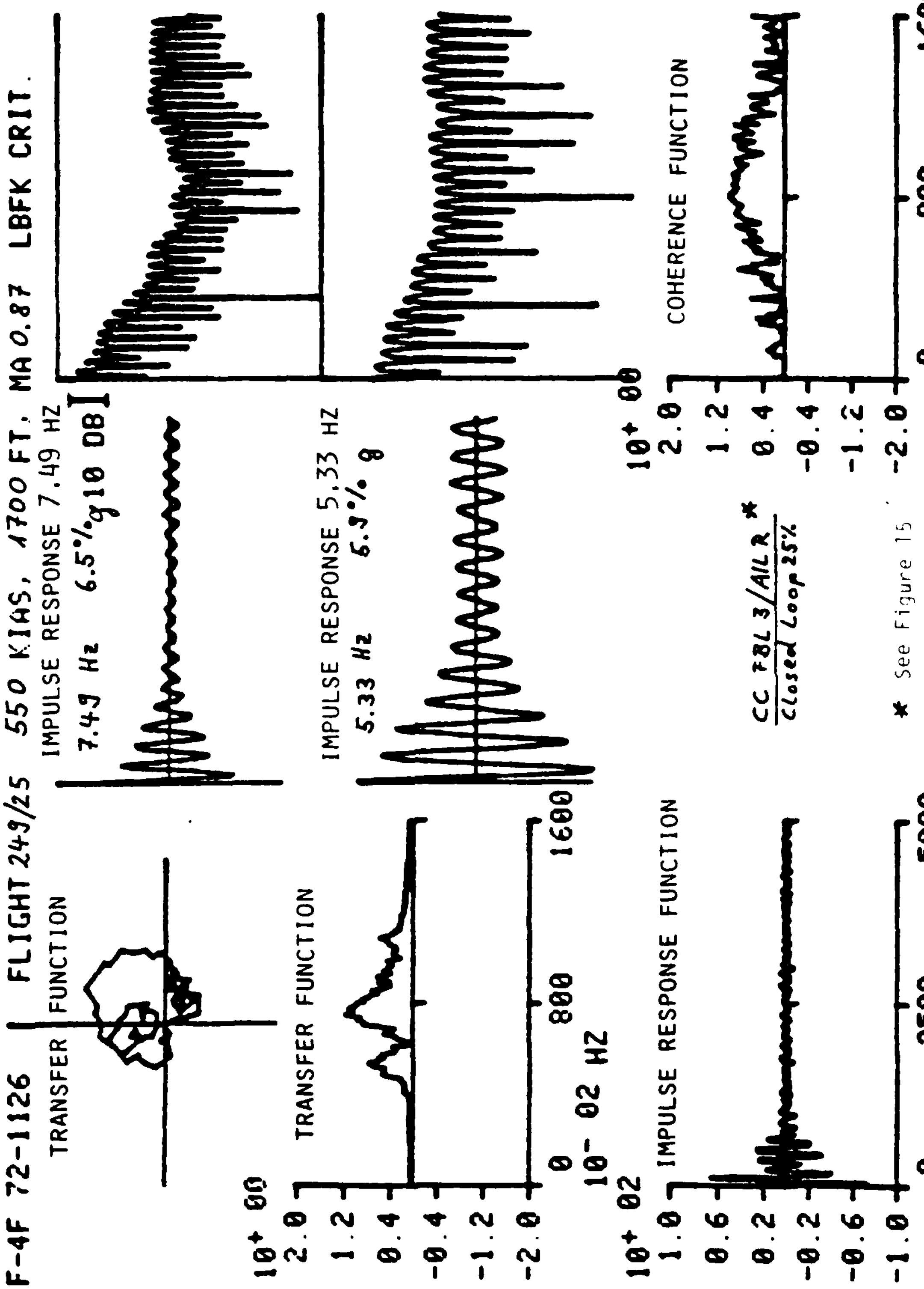


Figure 16. Data Evaluation (Damping, Frequency), M = .87

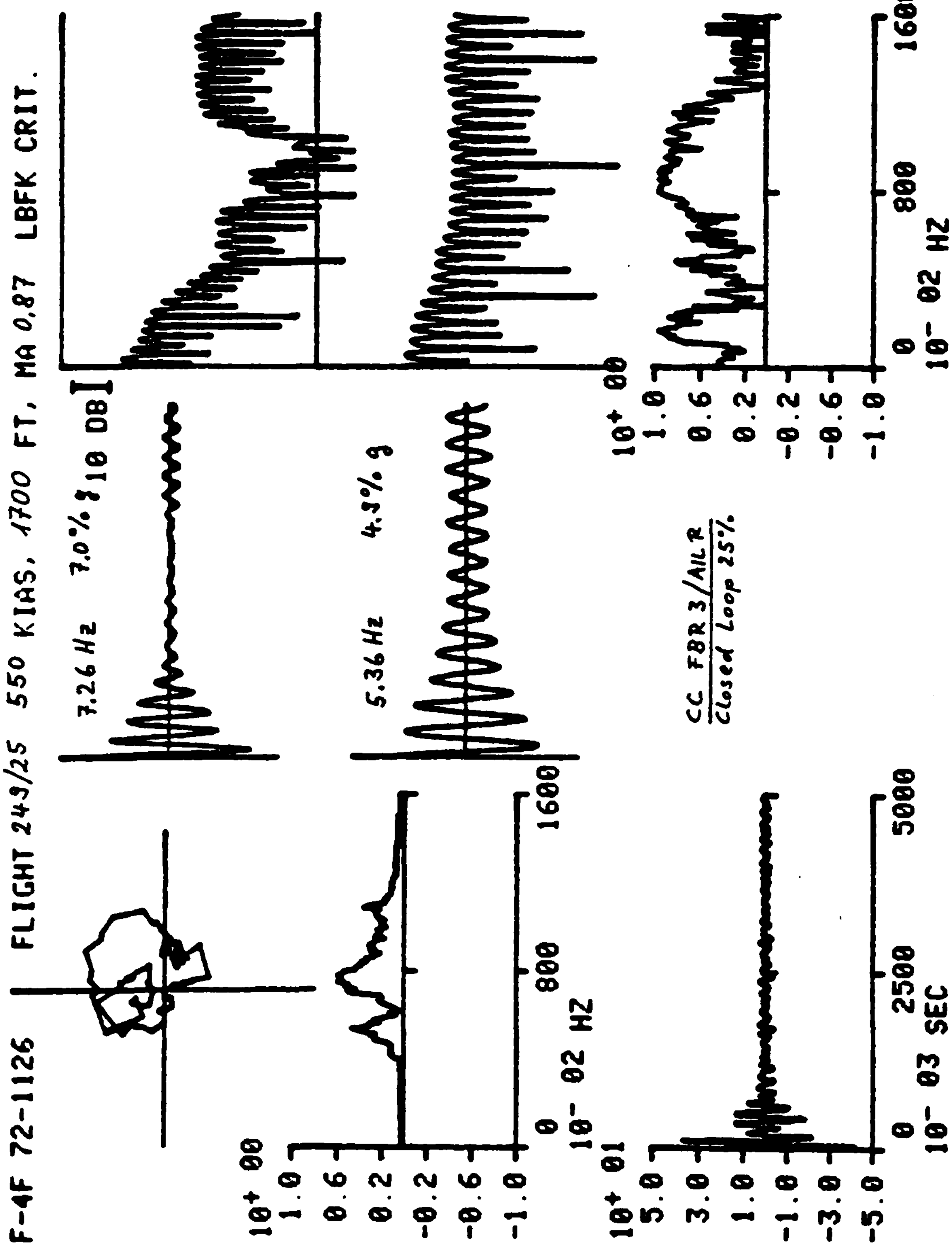


Figure 17. Data Evaluation (Damping, Frequency), M = .87

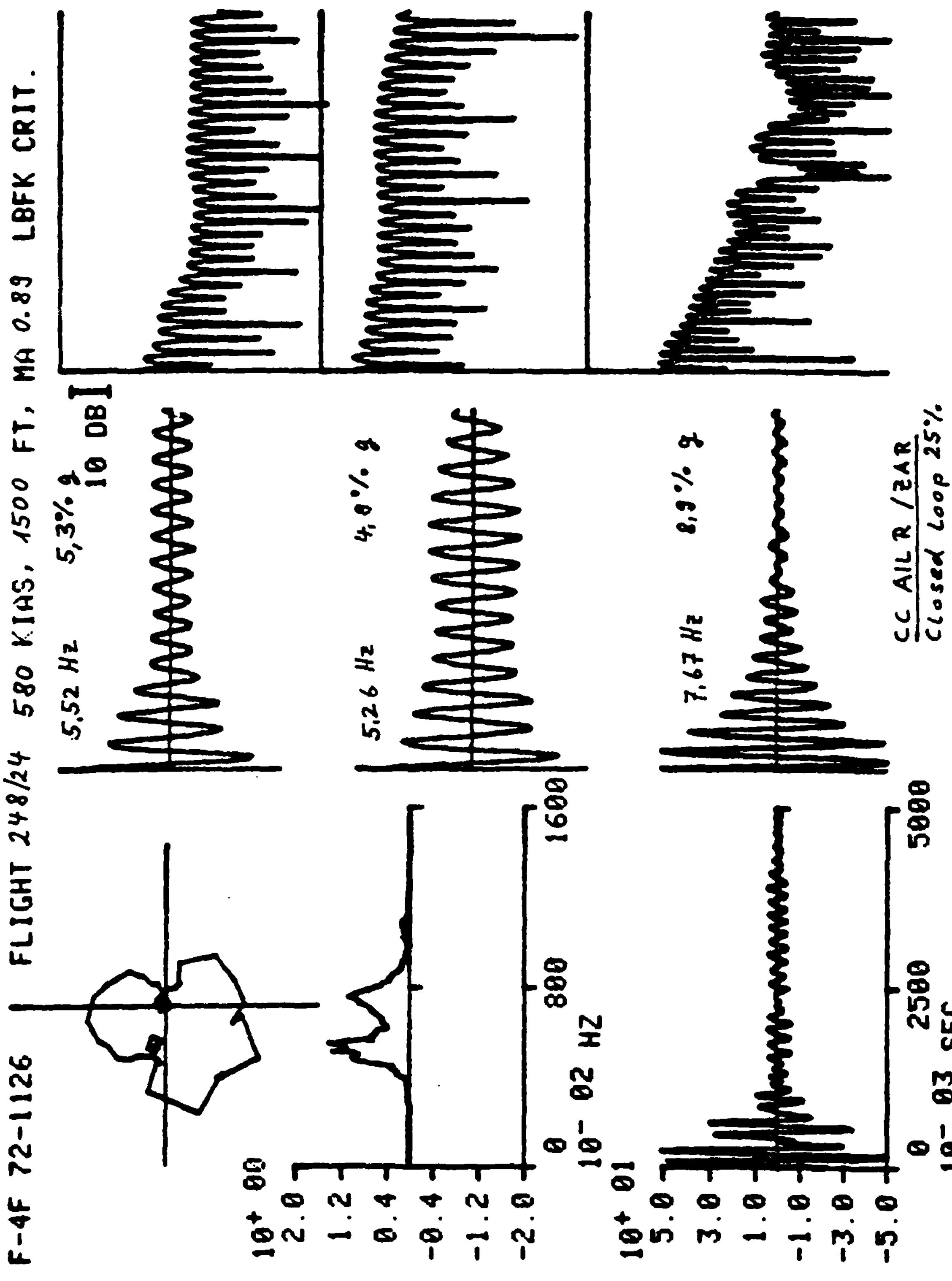


Figure 18. Data Evaluation (Damping, Frequency), M = .89

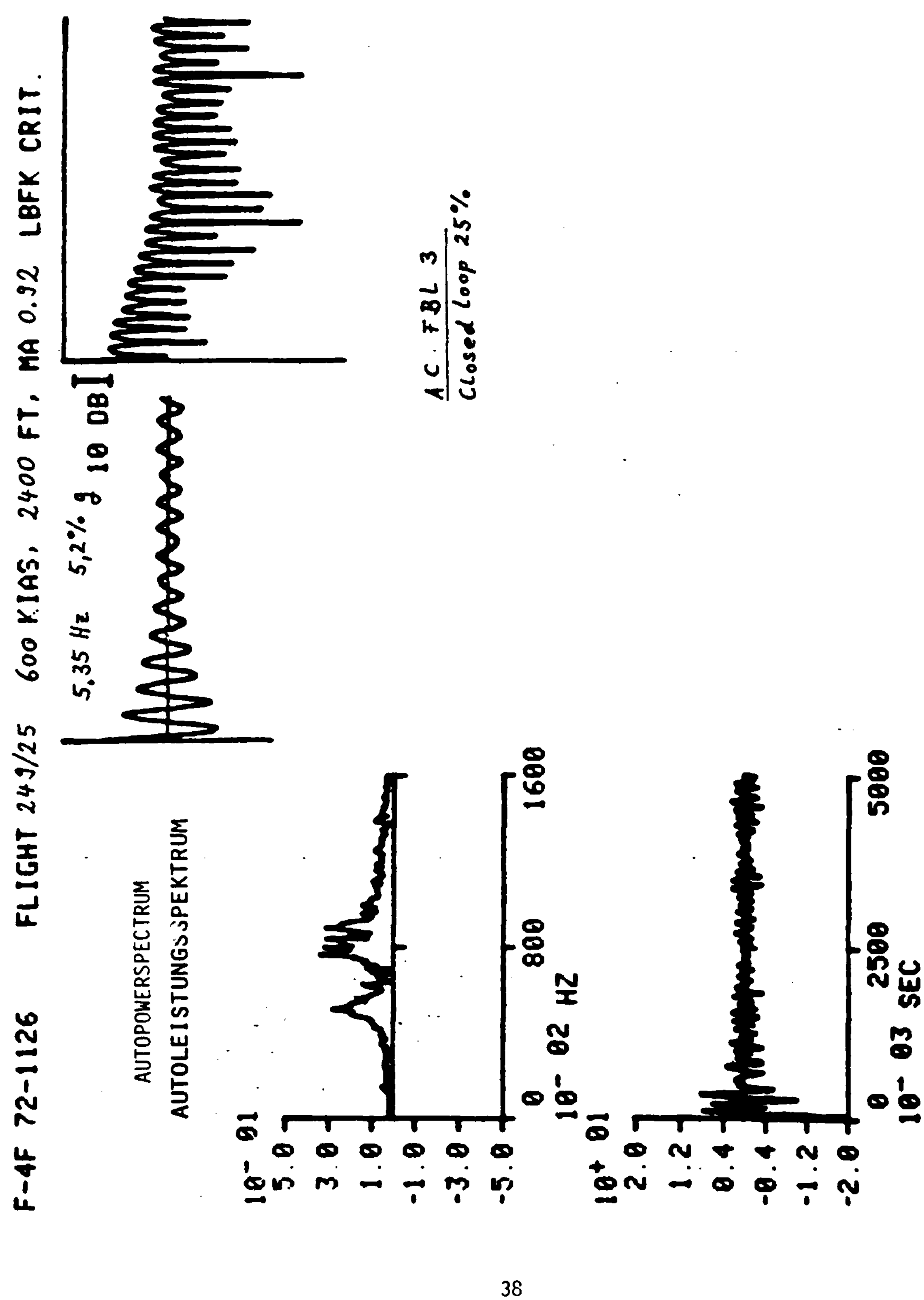


Figure 19. Data Evaluation (Damping, Frequency), M = .92

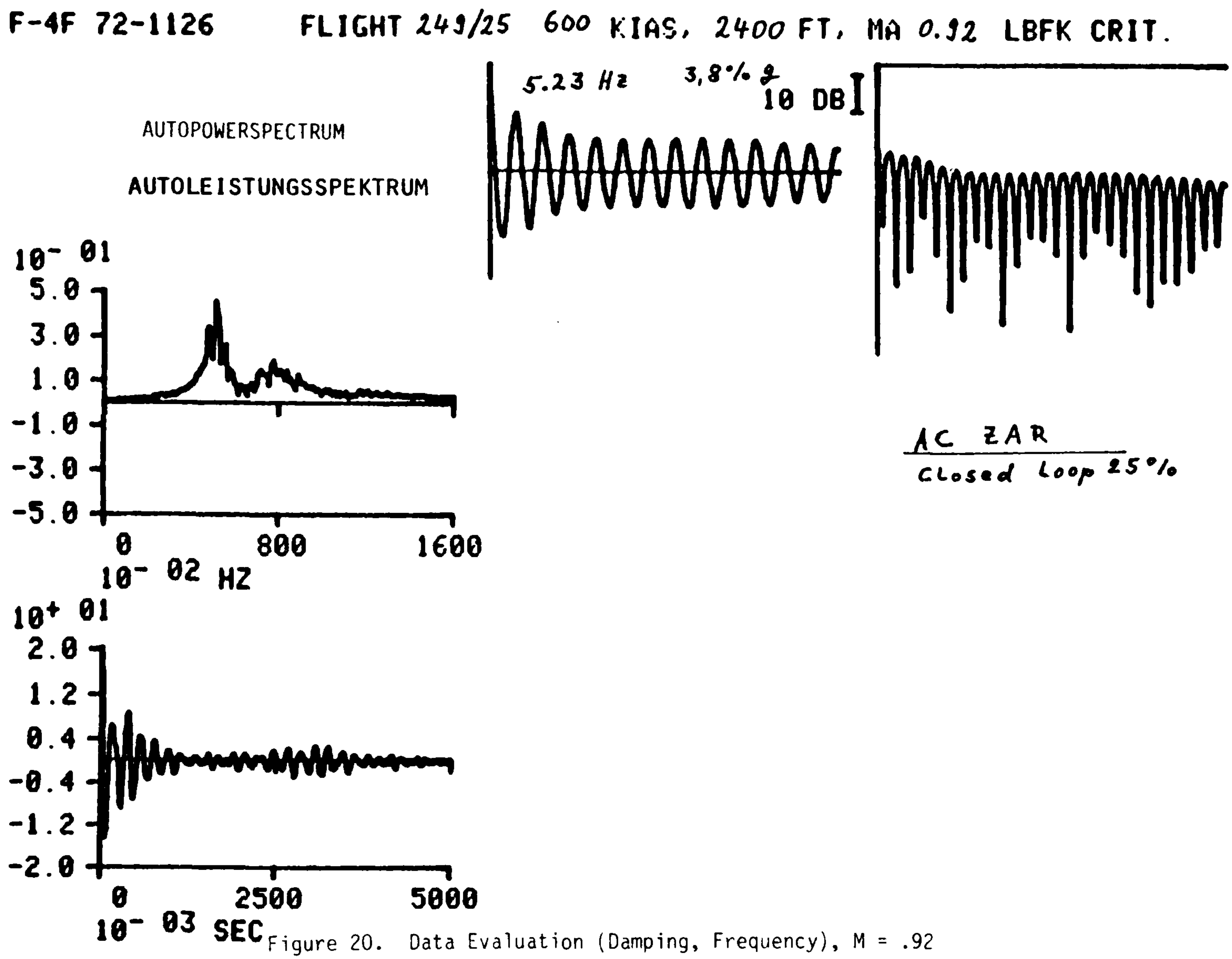


Figure 20. Data Evaluation (Damping, Frequency), M = .92

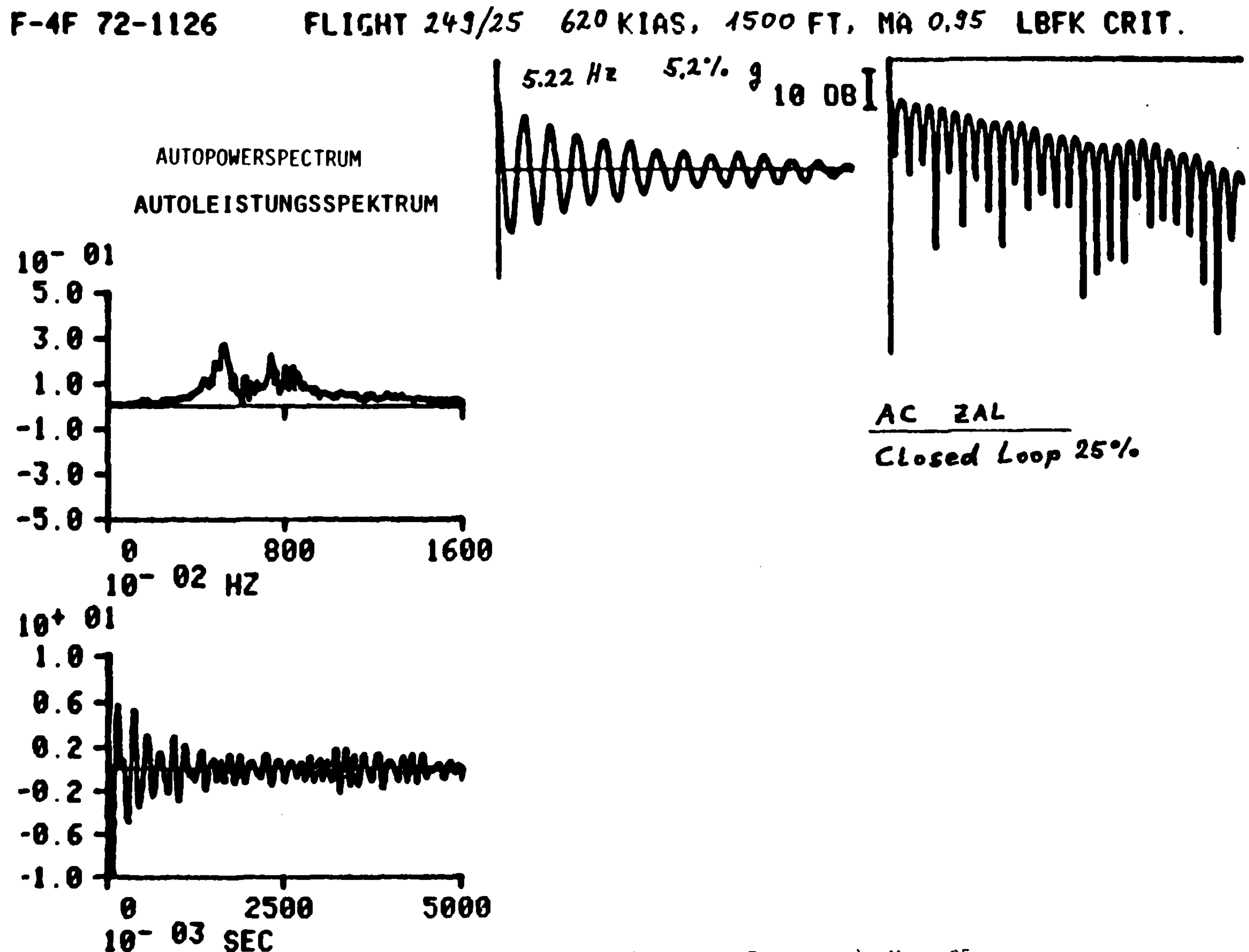


Figure 21. Data Evaluation (Damping, Frequency), M = .95

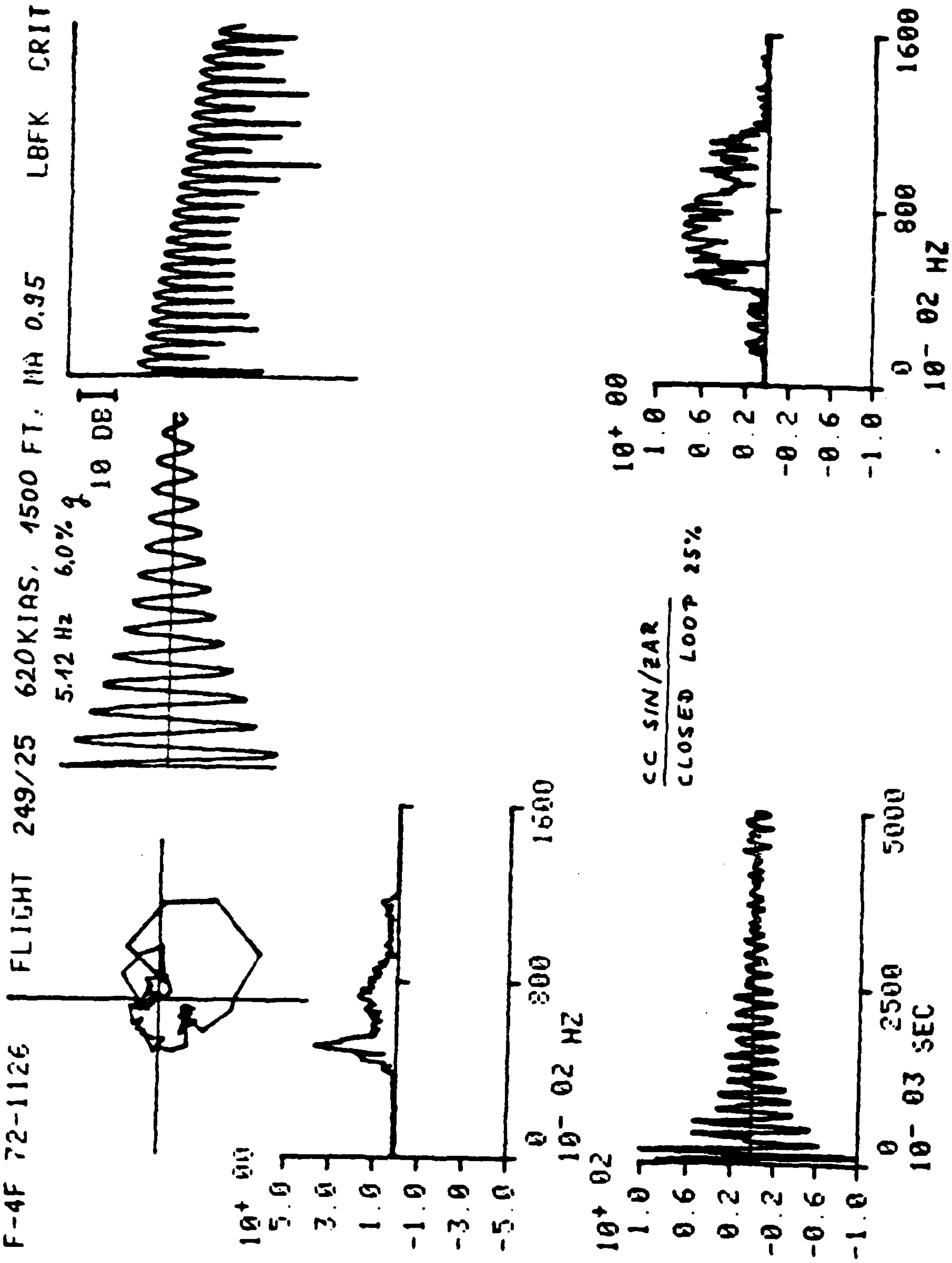


Figure 22. Data Evaluation (Damping, Frequency), M = .95

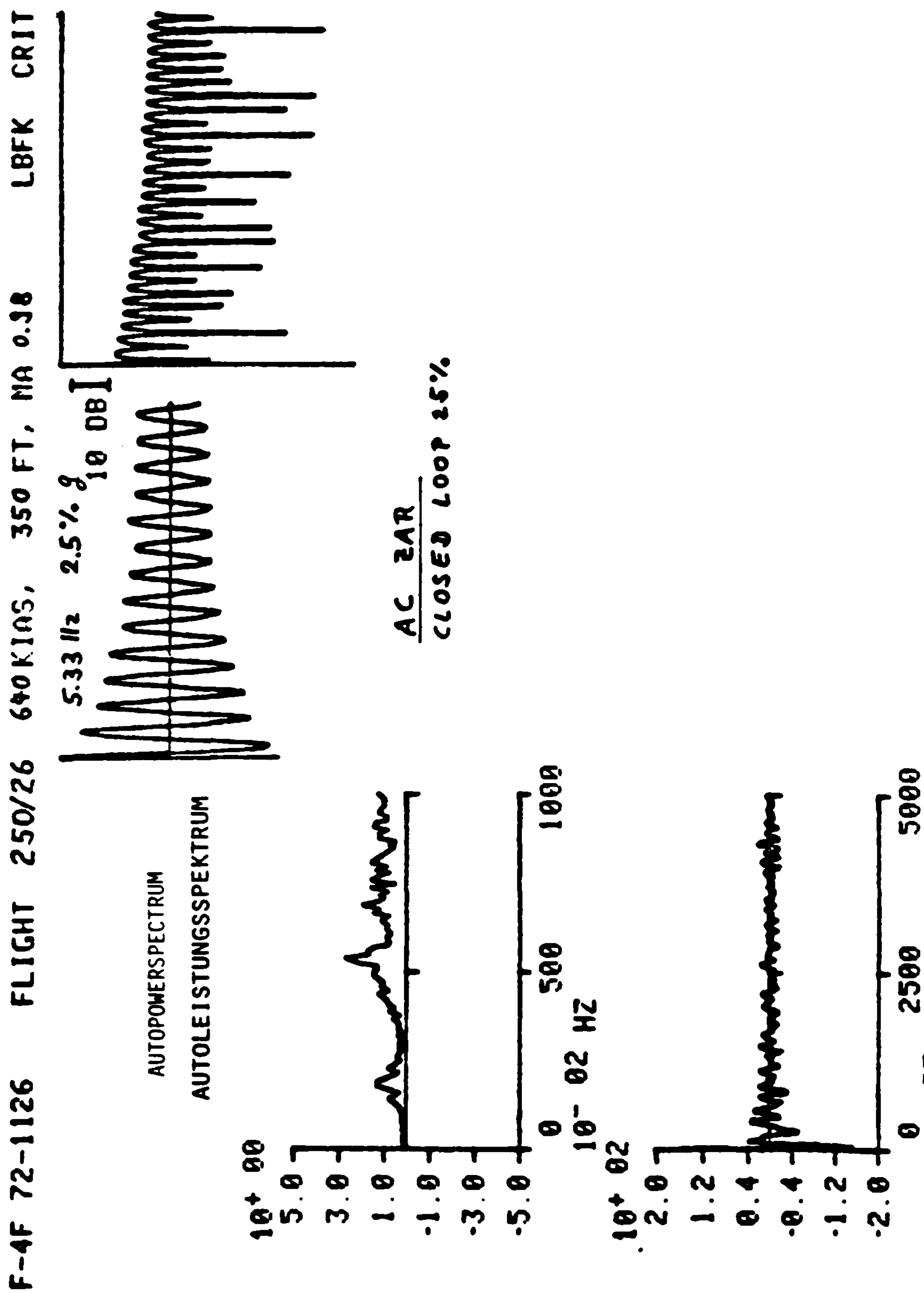


Figure 23. Data Evaluation (Damping, Frequency), M = .98

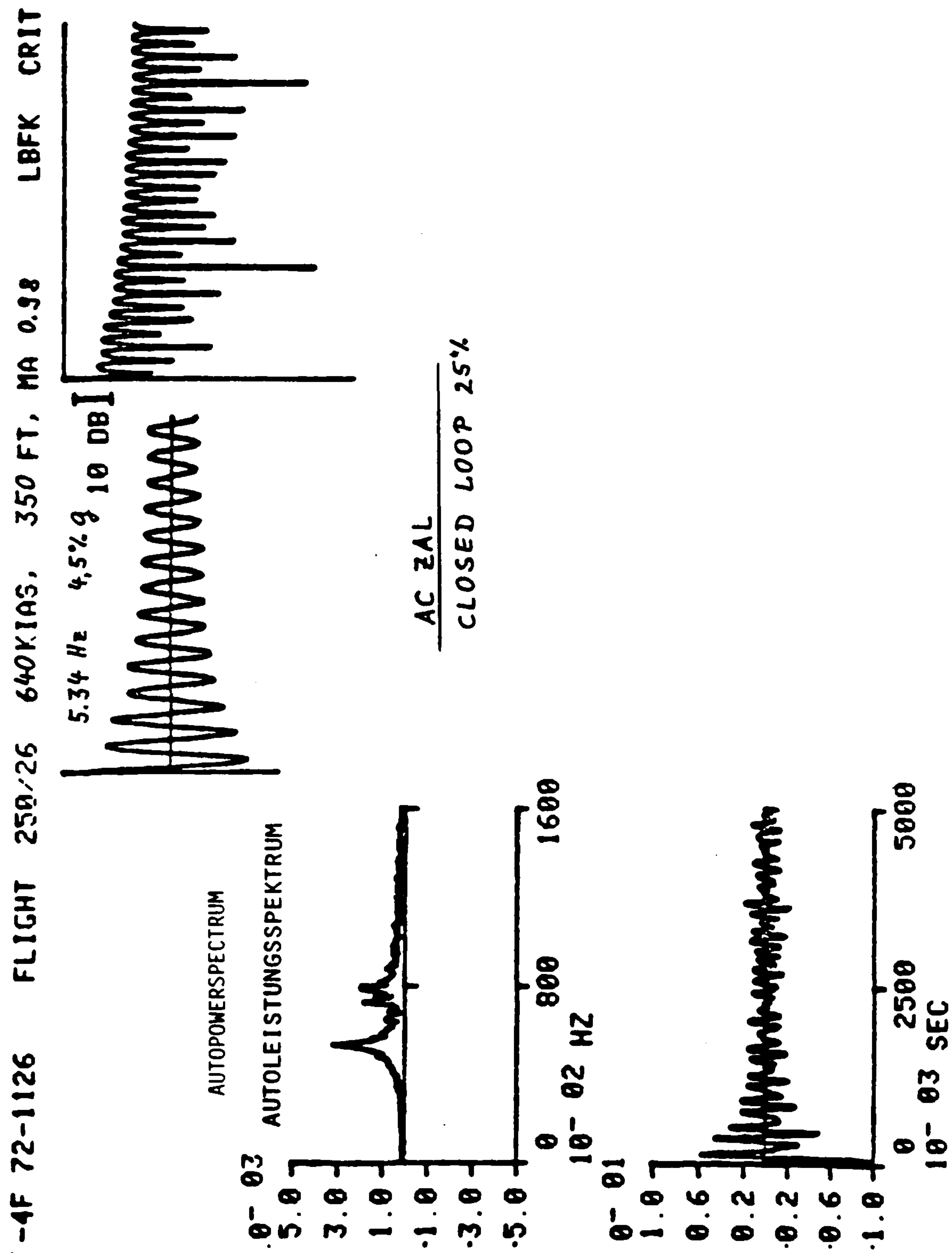


Figure 24. Data Evaluation (Damping, Frequency), M = .98

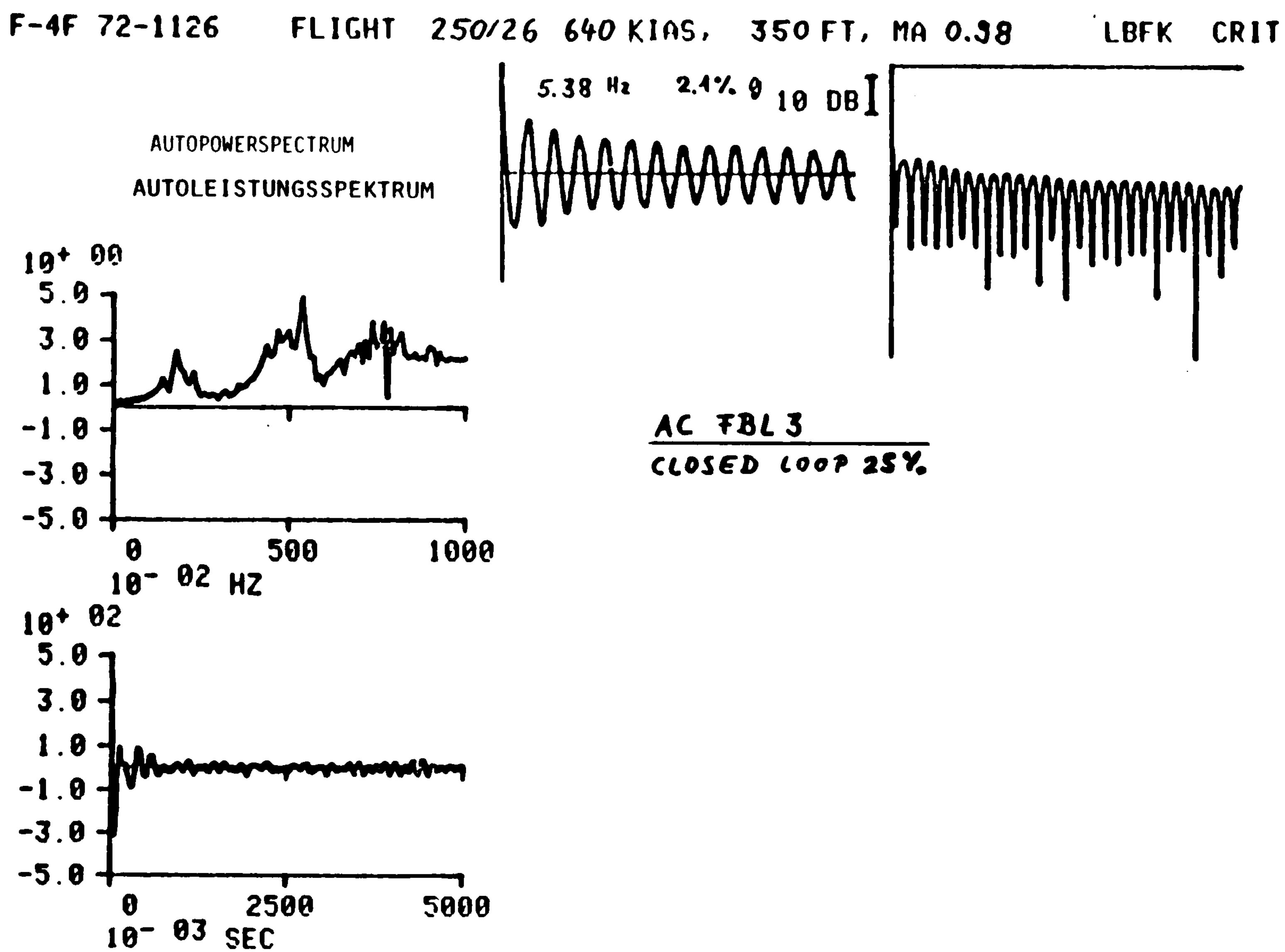


Figure 25. Data Evaluation (Damping, Frequency), M = .98

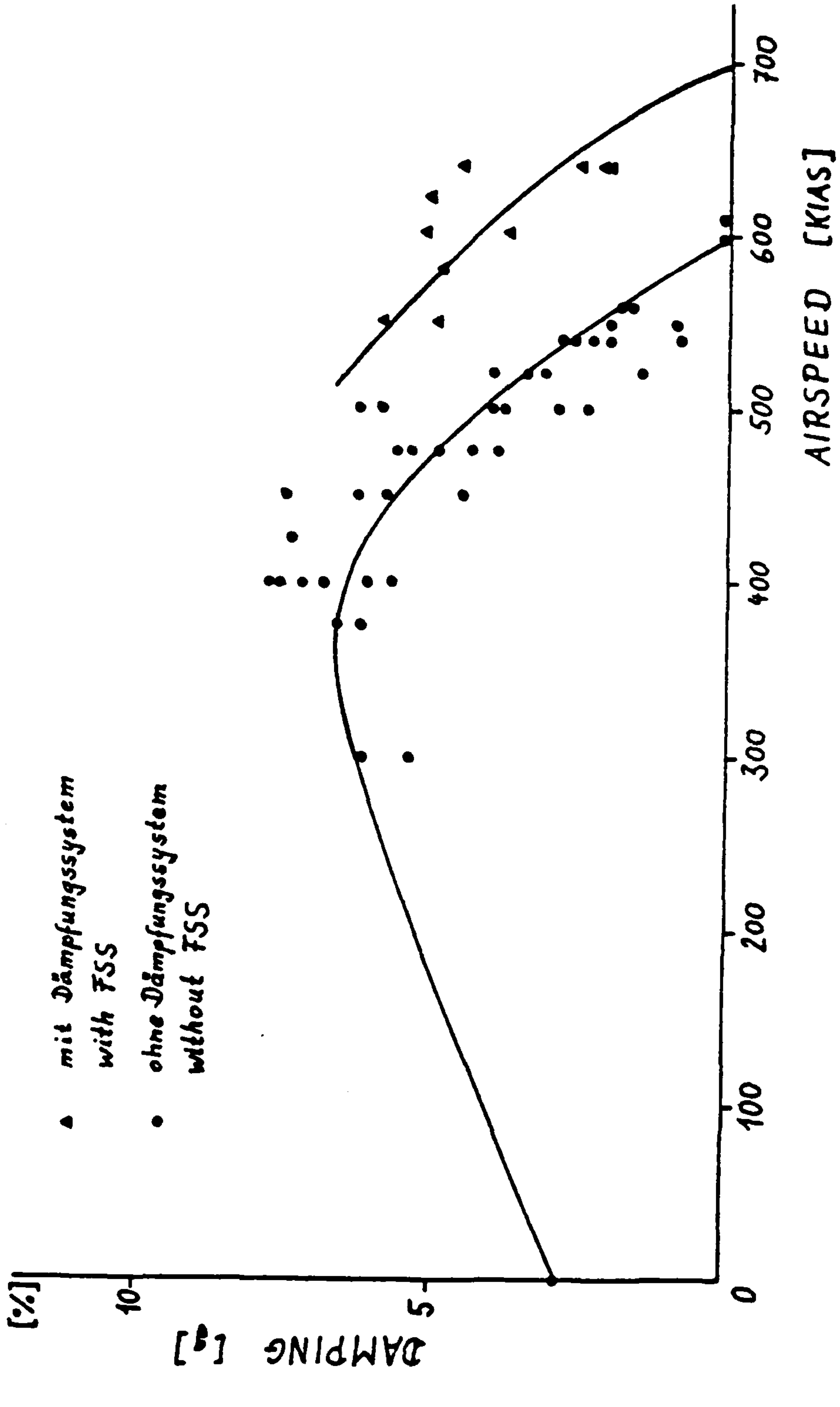


Figure 26. Possible Increase of Flutter Speed by the Active Flutter Suppression System

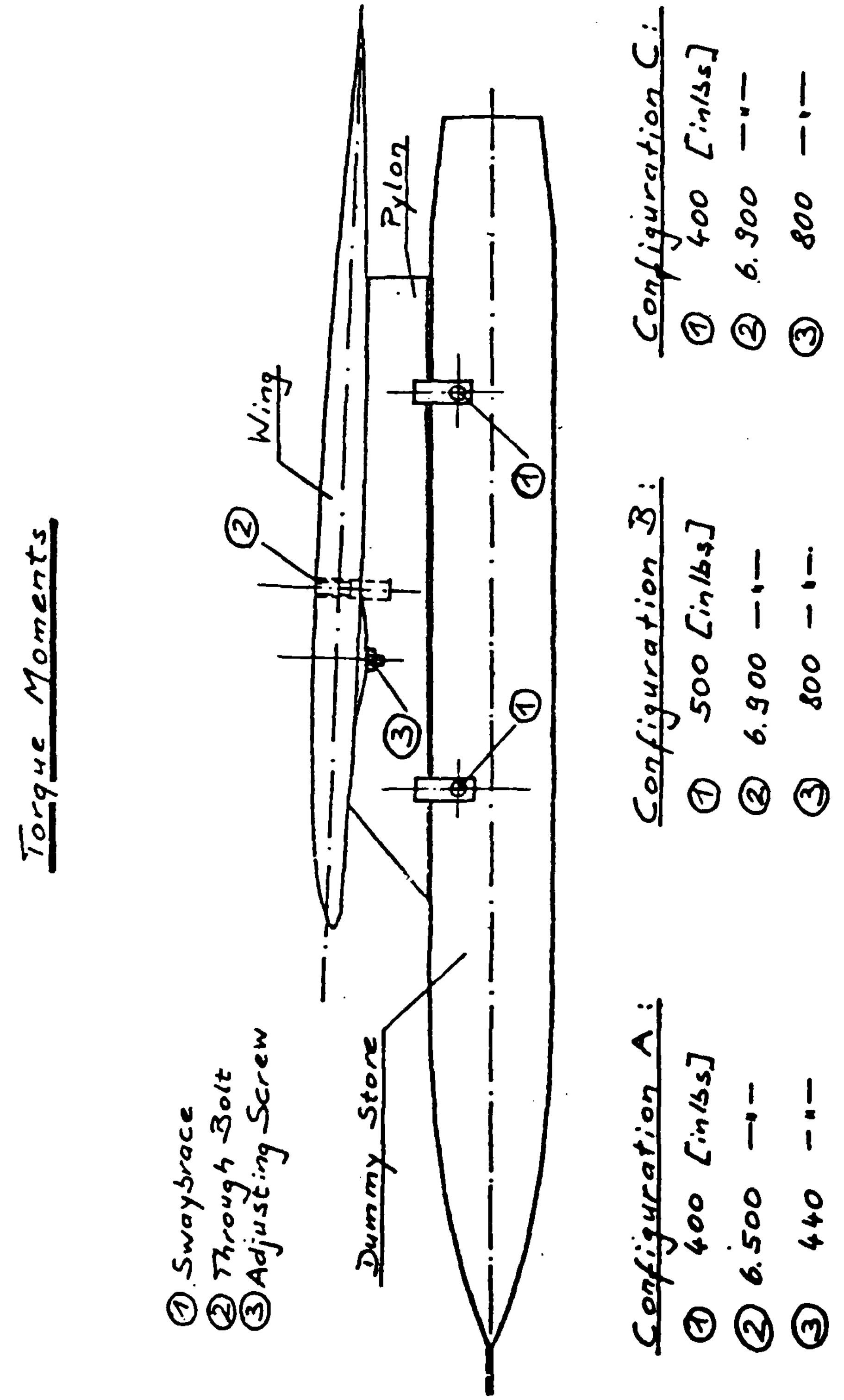


Figure 27. Pylon-Wing-Store Attachment

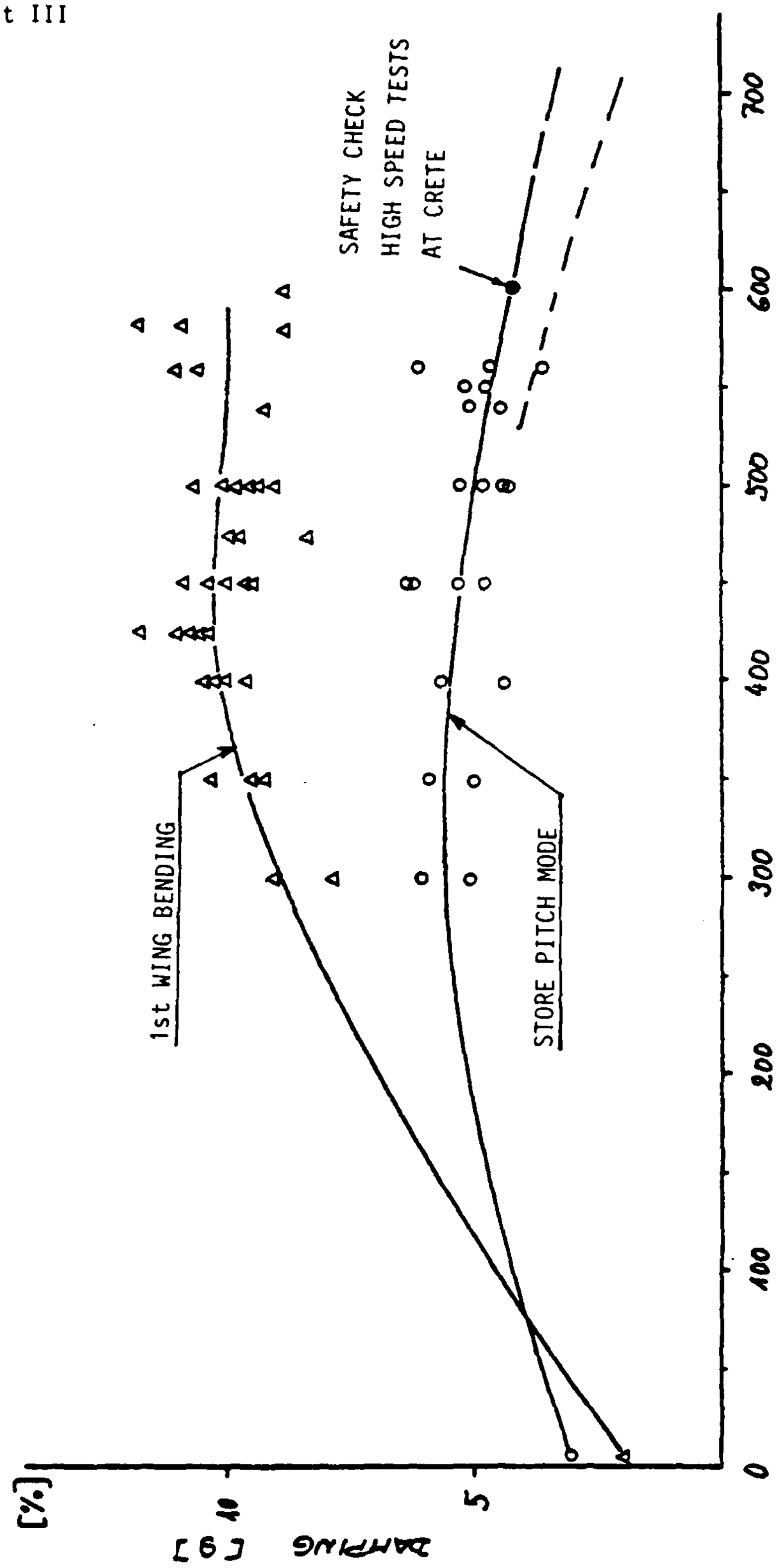


Figure 28. Possible Increase of the Flutter Speed using the Flutter Stopper

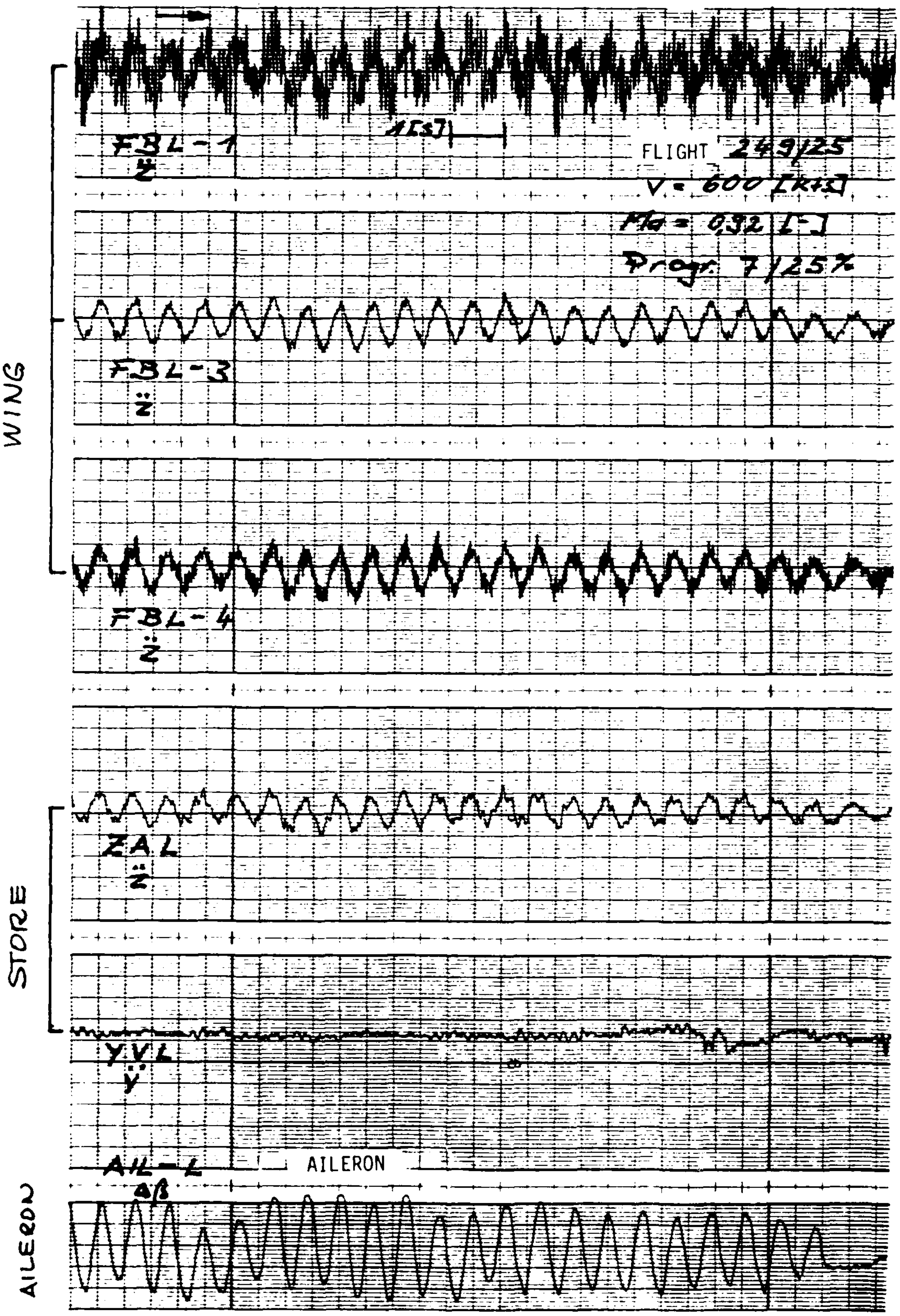


Figure 29. Time History of the Rigid Body Mode

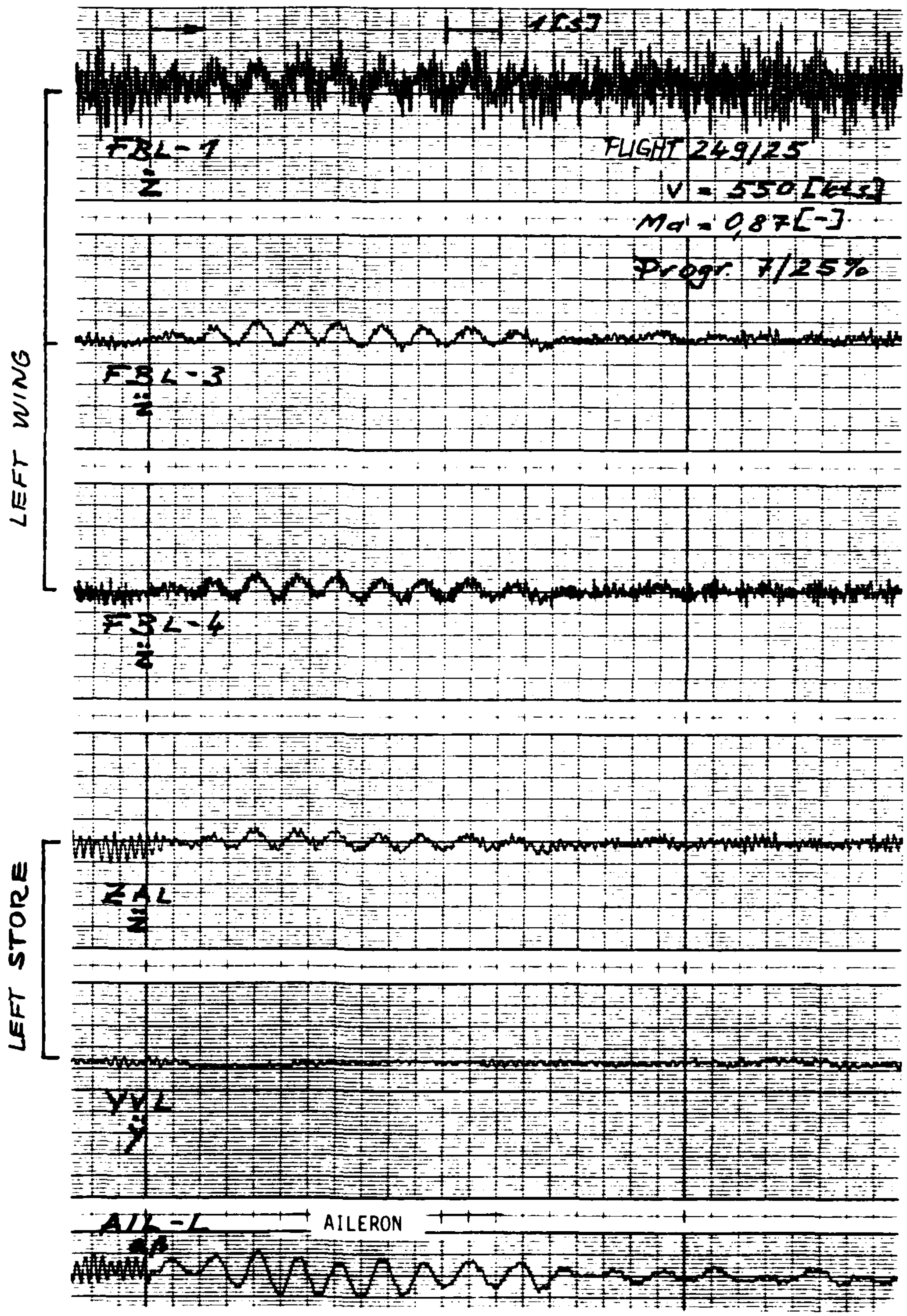


Figure 30. Time History of the Rigid Body Mode

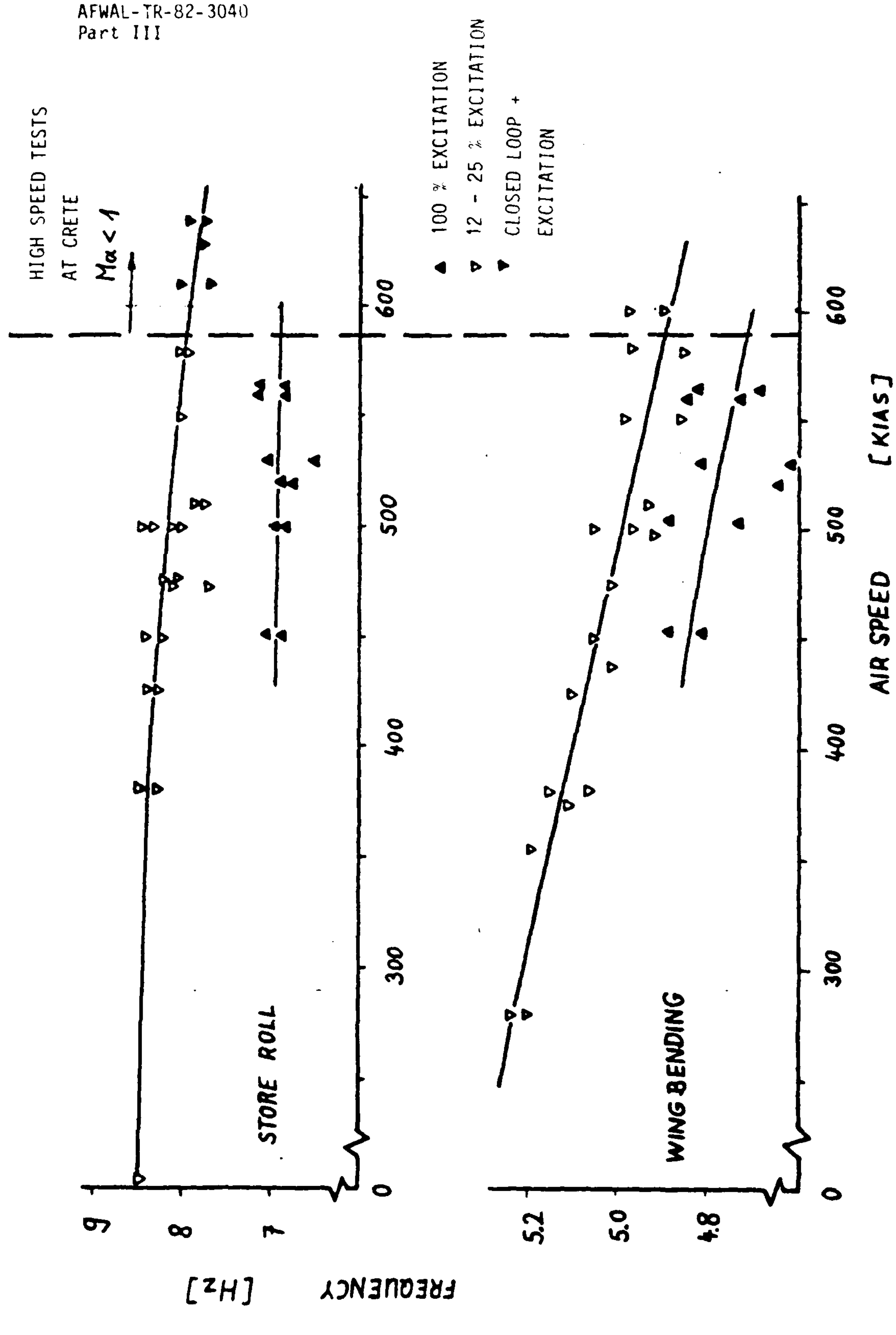


Figure 31. Frequency Shifts Caused by Structural Non-Linearities

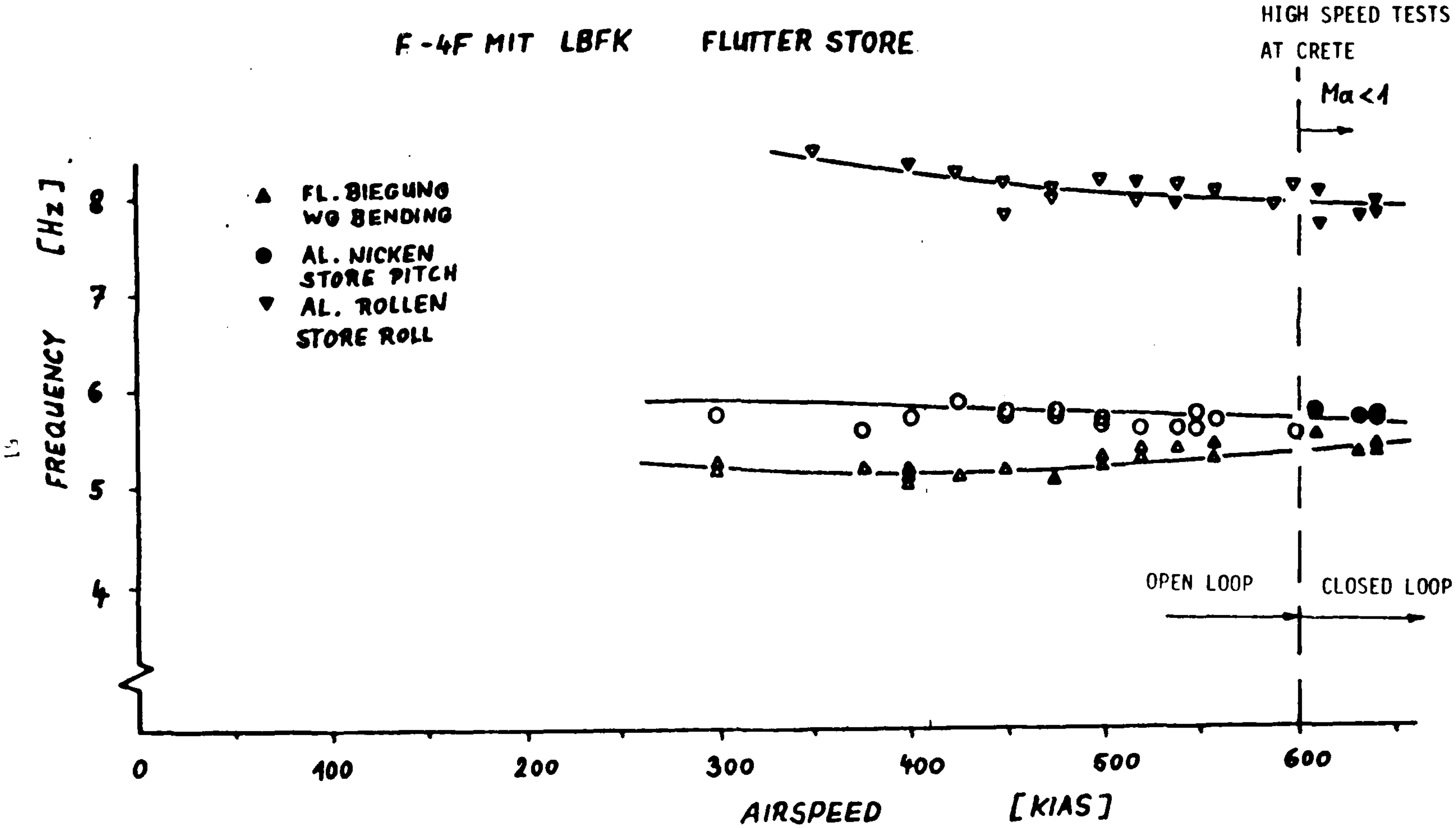


Figure 32. Frequency Shifts Caused by Structural Non-Linearities

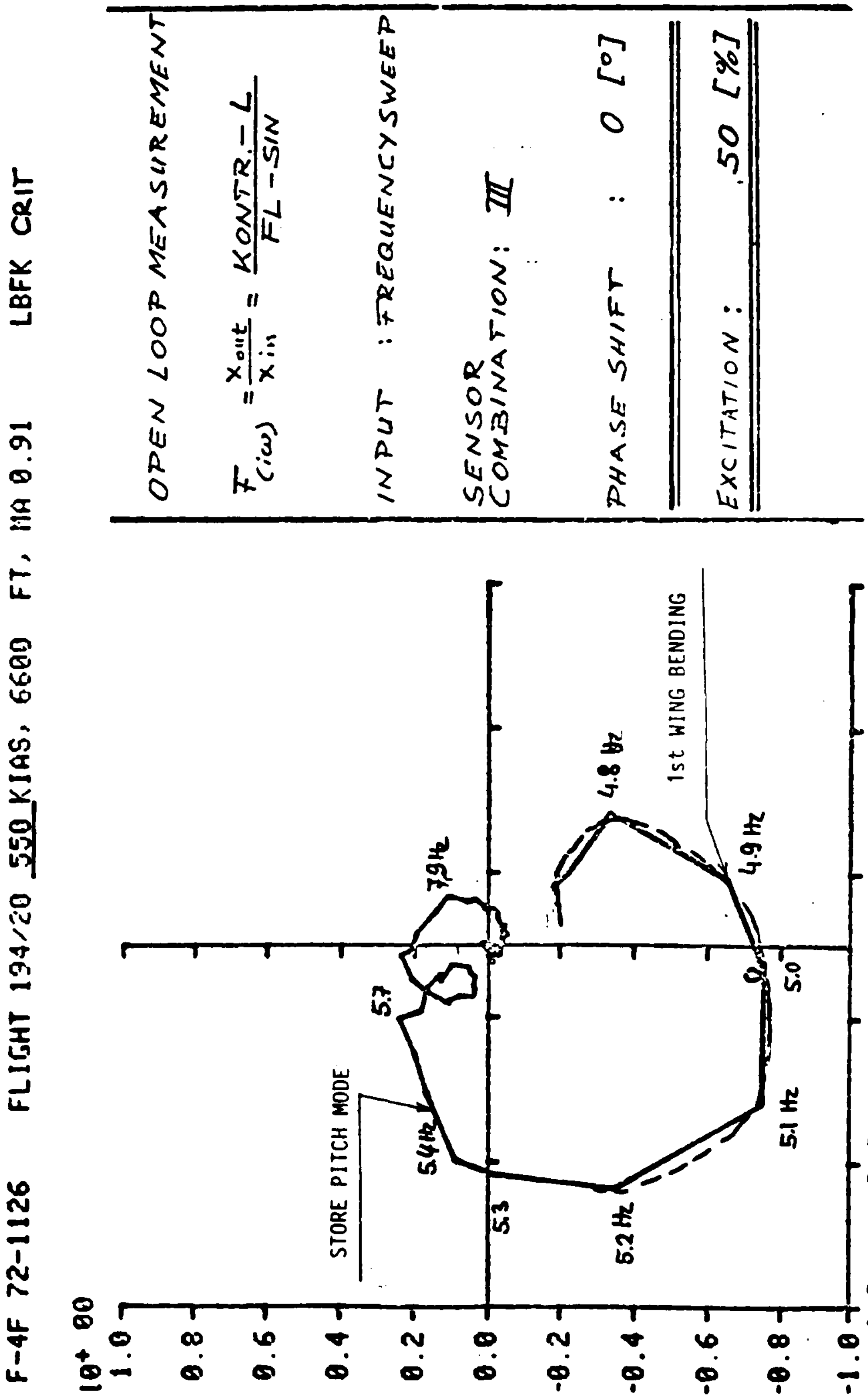


Figure 33. Comparison of Open Loop Measurement with Various Excitation Levels

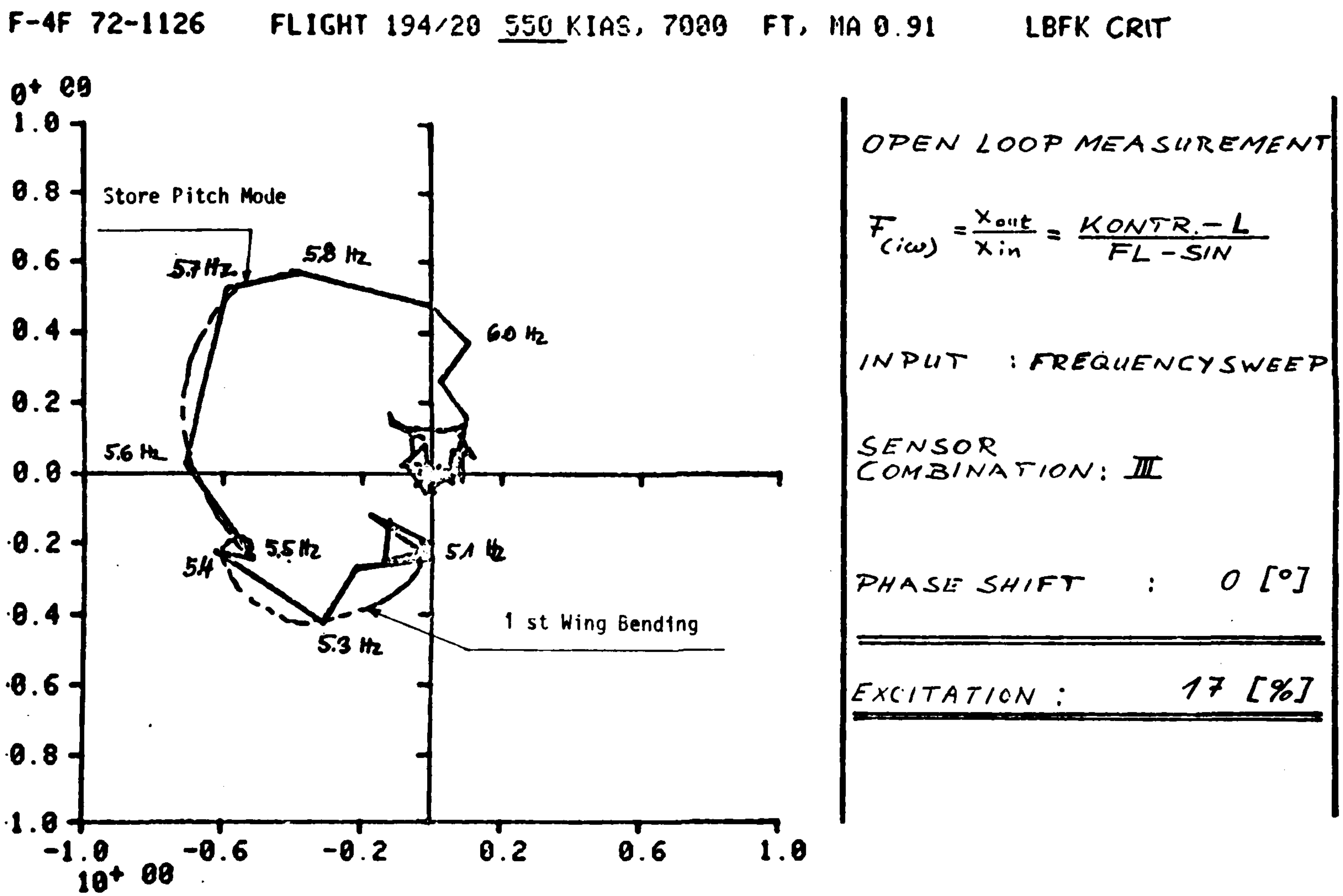


Figure 34. Comparison of Open Loop Measurement with Various Excitation Levels

Table 1. Modified Control Law

SENSOR COMBINATION	MODIFIED CONTROL LAW				PHASE CORRECTION
	K_φ	K_Θ	$K_{\dot{\varphi}}$	$K_{\dot{\Theta}}$	
$\varphi \cong \frac{③ + ④}{2l}$	−1.32	−3.48	−0.06	−0.0214	0°
$\Theta \cong \frac{③ - ④}{l}$	−1.44	−1.49	−0.06	−0.06	30°

Table 2. Flight Test Points

FLIGHT DATA				CONFIGURATION				FLIGHT TEST		
FLIGHT	ALT. [ft]	SPEED [KIAS]	Ma	STORE	ACTUATOR	SENS. COMB.	PYLON TORQUE MOM.	TEST PROGR. 1	TEST PROGR. 7	REMARKS
247/23	1600	410	0,64	CRITICAL	N.W. H.G.	II	C	50%	./.	FREQU. SWEEP 4-16 [Hz]
-"-	1600	400	0,62	-"-	-"-	-"-	-"-	50%	25%	
-"-	1600	400	0,62	-"-	-"-	-"-	-"-	25%	50%	
-"-	1700	500	0,77	-"-	-"-	-"-	-"-	25%	./.	
-"-	500	500	0,77	-"-	-"-	-"-	-"-	./.	25%	
-"-	1400	560	0,87	-"-	-"-	-"-	-"-	25%	./.	
-"-	1200	550	0,85	-"-	-"-	-"-	-"-	./.	25%	
-"-	500	580	0,90	-"-	-"-	-"-	-"-	25%	./.	
248/24	800	550	0,85	-"-	-"-	-"-	-"-	25%	./.	
-"-	1200	580	0,89	-"-	-"-	-"-	-"-	25%	./.	
-"-	1500	580	0,89	-"-	-"-	-"-	-"-	./.	25%	
-"-	1400	605	0,90	-"-	-"-	-"-	-"-	25%	./.	
249/25	1700	550	0,87	-"-	-"-	-"-	-"-	./.	25%	
-"-	2400	600	0,92	-"-	-"-	-"-	-"-	./.	25%	
-"-	1500	620	0,95	-"-	-"-	-"-	-"-	./.	25%	FREQU. SWEEP 4-16 [Hz]

FLIGHT DATA				CONFIGURATION				FLIGHT TEST		
FLIGHT	ALT. [ft]	SPEED [KIAS]	Ma	STORE	ACTU-ATOR	SENS. COMB.	PYLON TORQUE MOM.	TEST PROGR. 1	TEST PROGR. 7	REMARKS
250/26	500	630	0,97	CRITICAL	N.W. H.G	—"—	C	12 %	./.	FREQU. SWEEP 4 - 16 [Hz]
—"—	350	640	0,98	—"—	—"—	—"—	—"—	./.	25 %	
—"—	500	650	0,99	—"—	—"—	—"—	—"—	./.	25 %	
251/27	700	550	0,85	WITHOUT	—"—	—"—	—"—	50%	./.	
—"—	350	600	0,90	—"—	—"—	—"—	—"—	50%	./.	
—"—	800	630	0,95	—"—	—"—	—"—	—"—	50%	./.	FREQU. SWEEP 4 - 16 [Hz]

Table 3. List of Signals Recorded

TAPE CHANNEL	SENSOR CODE	PARAMETER NR
1	ZAL	184
2	ZAR	187
3	FBL-2	128
4	FBR-2	134
5	KONTR-L	194
6	KONTR-R	195
7	AIL-L	019
8	AIL-R	020
9	FL-SIN	145
10	FBR-3	170
11	FBL-3	129
12	YVR	189
13	IRIG B	
14	SPRACHE/VOICE	

ME

8